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# Evaluation of Generic 3X Upper Bound Factor Used in Reconstructing External Gamma Doses to Military Participants at Atmospheric Nuclear Weapon Tests



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This report discusses the adequacy of a generic 3X upper bound factor used by the Defense Threat Reduction Agency, Nuclear Test Personnel Review in reconstructing external personnel gamma doses. Comparisons are performed between reconstructed doses with relevant film badge readings in evaluating the adequacy of applying a 3x upper bound factor to reconstructed mean doses or point estimates of doses with no uncertainty. The use of the 3X upper bound factor was usually found adequate in cases of land exposure in either the Nevada Test Site or Pacific Proving Ground. In the case of shipboard exposures in the Pacific Proving Ground, less adequacy was noted, and further investigation was recommended. Finally, a recommendation was made that doses to unbadged shipboard personnel should be assigned on the basis of badge readings for other participants on that ship, rather than a reconstructed dose.

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Conversion Factors for U.S. Customary to metric (SI) units of measurement.

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TO GET ⟵ BY ⟵ DIVIDE

| | | |
|---|---|---|
| angstrom | 1.000 000 x E -10 | meters (m) |
| atmosphere (normal) | 1.013 25 x E +2 | kilo pascal (kPa) |
| bar | 1.000 000 x E +2 | kilo pascal (kPa) |
| barn | 1.000 000 x E -28 | meter$^2$ (m$^2$) |
| British thermal unit (thermochemical) | 1.054 350 x E +3 | joule (J) |
| calorie (thermochemical) | 4.184 000 | joule (J) |
| cal (thermochemical/cm$^2$) | 4.184 000 x E -2 | mega joule/m$^2$ (MJ/m$^2$) |
| curie | 3.700 000 x E +1 | *giga bacquerel (GBq) |
| degree (angle) | 1.745 329 x E -2 | radian (rad) |
| degree Fahrenheit | $t_k = (t^\circ f + 459.67)/1.8$ | degree kelvin (K) |
| electron volt | 1.602 19 x E -19 | joule (J) |
| erg | 1.000 000 x E -7 | joule (J) |
| erg/second | 1.000 000 x E -7 | watt (W) |
| foot | 3.048 000 x E -1 | meter (m) |
| foot-pound-force | 1.355 818 | joule (J) |
| gallon (U.S. liquid) | 3.785 412 x E -3 | meter$^3$ (m$^3$) |
| inch | 2.540 000 x E -2 | meter (m) |
| jerk | 1.000 000 x E +9 | joule (J) |
| joule/kilogram (J/kg) radiation absorbed dose | 1.000 000 | Gray (Gy) |
| kilotons | 4.183 | terajoules |
| kip (1000 lbf) | 4.448 222 x E +3 | newton (N) |
| kip/inch$^2$ (ksi) | 6.894 757 x E +3 | kilo pascal (kPa) |
| ktap | 1.000 000 x E +2 | newton-second/m$^2$ (N-s/m$^2$) |
| micron | 1.000 000 x E -6 | meter (m) |
| mil | 2.540 000 x E -5 | meter (m) |
| mile (international) | 1.609 344 x E +3 | meter (m) |
| ounce | 2.834 952 x E -2 | kilogram (kg) |
| pound-force (lbs avoirdupois) | 4.448 222 | newton (N) |
| pound-force inch | 1.129 848 x E -1 | newton-meter (N-m) |
| pound-force/inch | 1.751 268 x E +2 | newton/meter (N/m) |
| pound-force/foot$^2$ | 4.788 026 x E -2 | kilo pascal (kPa) |
| pound-force/inch$^2$ (psi) | 6.894 757 | kilo pascal (kPa) |
| pound-mass (lbm avoirdupois) | 4.535 924 x E -1 | kilogram (kg) |
| pound-mass-foot$^2$ (moment of inertia) | 4.214 011 x E -2 | kilogram-meter$^2$ (kg-m$^2$) |
| pound-mass/foot$^3$ | 1.601 846 x E +1 | kilogram-meter$^3$ (kg/m$^3$) |
| rad (radiation dose absorbed) | 1.000 000 x E -2 | **Gray (Gy) |
| roentgen | 2.579 760 x E -4 | coulomb/kilogram (C/kg) |
| shake | 1.000 000 x E -8 | second (s) |
| slug | 1.459 390 x E +1 | kilogram (kg) |
| torr (mm Hg, $0^\circ$ C) | 1.333 22 x E -1 | kilo pascal (kPa) |

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The gray (Gy) is the SI unit of absorbed dose.

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# 1. INTRODUCTION

The Defense Threat Reduction Agency (DTRA) is responsible for providing estimates of radiation doses that were received by military participants at atmospheric nuclear weapons tests during the period 1945–1962. Many participants received external exposure to gamma radiation (photons), including initial gamma radiation that was emitted during the first minute after a nuclear detonation and, more commonly, residual gamma radiation that was emitted at later times in radioactive decay of fission and activation products and other debris from a weapon.

External exposure to gamma radiation often was monitored using film badges worn by participants. However, many participants did not wear film badges during periods of exposure. In those cases, external gamma doses must be estimated using more indirect methods of dose reconstruction. For example, many reconstructions of external gamma dose have been based on external exposure rates in the environment or on ships that were measured in radiation surveys shortly after a detonation, extrapolation or interpolation of measured exposure rates in time and space, and assumptions about locations and times of exposure.

## 1.1 Policies on Estimating Upper Bounds of Reconstructed External Gamma Doses

In accordance with a policy of the Nuclear Test Personnel Review (NTPR) Program specified in Title 32, Part 218 of the Code of Federal Regulations (32 CFR Part 218), reconstructions of external gamma dose should provide estimates of mean doses and upper bounds, where upper bounds should be at least upper 95% confidence limits when uncertainties in estimating dose are taken into account; i.e., upper bounds should not underestimate doses to at least 95% of all participants. Upper bounds are more important than mean doses because, as specified in regulations of the U.S. Department of Veterans Affairs in 38 CFR 3.311, they are used in adjudicating claims for compensation for cancers and other radiogenic diseases when an evaluation of disease causation is required.

Prior to July 2003, upper bounds of reconstructed external gamma doses relative to mean doses were estimated on a scenario-specific basis. For example, when participants who did not wear film badges were members of a military unit that engaged in well documented activities at a particular atmospheric test or tests and there was no indication that they engaged in other

activities apart from their unit that could have resulted in significant radiation exposure, means and upper bounds of external gamma doses often were estimated on the basis of a unit dose reconstruction; i.e., all unbadged members of a unit were assigned the same mean dose and upper bound. The ratio of the upper bound to the mean dose, which we refer to as an "upper bound factor," generally was different in dose reconstructions for different military units.

In July 2003, DTRA issued Interim Guidance which specified that upper bounds of all reconstructed external gamma doses were to be calculated by multiplying reconstructed mean doses by a factor of three (Benavides, 2003). Use of a generic 3X upper bound factor[1] replaced the previous approach of estimating scenario-specific upper bounds. This provision of the Interim Guidance was based on a finding by a committee of the National Research Council (NRC) that, although reconstructed mean doses generally were valid, upper bounds often were underestimated (NRC, 2003); i.e., upper bounds of reconstructed external gamma doses often were too low to give at least upper 95% confidence limits of doses to participants. Use of a generic 3X upper bound factor in reconstructing external gamma doses is incorporated in current policies and procedures of the NTPR Program (DTRA, 2007; 2008).

### 1.2 Purpose of Report

The purpose of this report is to investigate whether use of a generic 3X upper bound factor, as specified in the Interim Guidance, is adequate to ensure that upper bounds of reconstructed external gamma doses are at least upper 95% confidence limits—i.e., whether use of a 3X upper bound factor gives upper bounds of reconstructed external gamma doses that do not underestimate doses to at least 95% of unbadged participants.

As described in Section 1.4, the approach taken in this investigation is to compare upper bounds of doses that are obtained by applying a 3X upper bound factor to reconstructed mean doses or point estimates of dose with no uncertainty given in unit dose reconstructions with upper bounds of distributions of film badge readings that apply to members of those units.[2] If the resulting upper bound of a reconstructed external gamma dose for a particular unit is greater

[1] The term "3X upper bound factor" is used in this report to denote that the upper bound of a reconstructed dose is assumed to be three times higher than the mean dose.

[2] Throughout this report, the term "upper bound" refers to an upper 95% confidence limit of a reconstructed dose or distribution of film badge readings, unless otherwise noted.

than doses indicated by at least 95% of the film badge readings for members of that unit, use of a 3X upper bound factor is considered to be adequate in that case.

Science Applications International Corporation (SAIC), which has developed methods of dose reconstruction used in the NTPR Program, is developing improved methods of uncertainty analysis for use in reconstructing mean external gamma doses and upper bounds. The intention is to replace a generic 3X upper bound factor with scenario-specific upper bounds that are based on an improved analysis of uncertainty in all parameters used in reconstructing external gamma doses. The evaluation of a generic 3X upper bound factor presented in this report does not consider SAIC's improved methods of uncertainty analysis but is concerned only with evaluating current practices of dose reconstruction, as specified in the 2003 Interim Guidance.

### 1.3 Basic Assumptions in Evaluating Adequacy of Generic 3X Upper Bound Factor

In evaluating the adequacy of a generic 3X upper bound factor in reconstructing external gamma doses on the basis of comparisons of reconstructed doses with distributions of relevant film badge readings, we have assumed that upper bounds that are obtained by applying a 3X upper bound factor to reconstructed mean doses or point estimates of dose with no uncertainty should be at least upper 95% confidence limits of *true* doses to participants. As a consequence of this assumption, the relationship between an exposure in roentgen (R) indicated by a film badge reading for a participant and the corresponding dose equivalent to the whole body in rem, which is the quantity calculated in dose reconstructions, is taken into account in evaluating the adequacy of a 3X upper bound factor. This is an important consideration when, in accordance with a policy of the NTPR Program (DTRA, 2007), the mean dose equivalent to the whole body in rem that is assigned to participants with badge readings is assumed to be equal to a badge reading (exposure) in R, even though badge readings in R generally overestimated dose to the whole body in rem. We refer to the ratio of a badge reading in R to the corresponding dose to the whole body in rem as a bias factor.

Biases in readings of film badges that were used during the atmospheric weapons testing program were estimated by a committee of the NRC (1989). Estimated biases in film badge readings at various operations at the Nevada Test Site (NTS) or Pacific Proving Ground (PPG)

are summarized in Table 1.1.[3] These bias factors have been taken into account in evaluating the adequacy of a 3X upper bound factor as described below.

**Table 1.1.** Overall bias factors in film badge readings at different operations at Nevada Test Site and Pacific Proving Ground[a]

| Operation | Film badge bias factor | Operation | Film badge bias factor |
|---|---|---|---|
| I. Nevada Test Site | | II. Pacific Proving Ground | |
| BUSTER-JANGLE | 1.5 | CROSSROADS | 1.5 |
| TUMBLER-SNAPPER | 2.1[b] | SANDSTONE | 1.5 |
| UPSHOT-KNOTHOLE | 1.1 | GREENHOUSE | 1.4 |
| TEAPOT | 1.1 | IVY | 1.5[c] |
| PLUMBBOB | 1.3 | CASTLE | 1.3 |
| | | WIGWAM | 1.3 |
| | | REDWING | 1.3 |
| | | HARDTACK I | 1.5 |
| | | DOMINIC I | 1.5 |

[a] See NRC (1989). Bias factor is ratio of deep-dose equivalent (rem) to exposure (R) recorded by film badges that were worn by participants. Deep-dose equivalent is assumed to give dose equivalent to whole body. Estimated bias in film badge readings at an operation is given only if reconstructed doses for military units at that operation are compared with relevant badge readings in this report.

[b] Bias factor applies to ground personnel only. Estimated bias factor for flight personnel is 1.8.

[c] Bias factor applies to ground personnel only. Estimated bias factor for flight personnel is 1.4.

[3] Several sources (categories) of bias in film badge readings were evaluated (NRC, 1989). The *laboratory* category includes several sources of bias in laboratory procedures to calibrate and process film and to interpret readings in terms of exposure, R. The *radiological* category includes biases due to (1) differences between the spectrum of photons to which a film was exposed and the spectrum used in calibrating the film, (2) wearing a film badge on the body when the film was calibrated freely in air, and (3) backscatter of photons by the body. The *environmental* category includes all biases related to the field environment in which film badges were exposed (e.g., exposure to moisture, light, high temperatures, and radioactive contamination). At all operations, a bias factor of 1.3 was applied to convert a badge reading in R, adjusted to account for operation-specific biases in recorded exposures due to laboratory, radiological, and environmental factors, to deep-dose equivalent. The total bias was obtained by combining the separate bias factors. The NRC (1989) report also gives estimated uncertainties in all bias factors; these uncertainties are not used in our evaluation of the adequacy of a 3X upper bound factor.

## 1.4 General Approach to Analysis

In this analysis, the adequacy of a 3X upper bound factor is evaluated on the basis of comparisons of reconstructed doses for specific military units at a particular test or tests at a particular operation with distributions of film badge readings for participants in those units. This approach conforms to the way dose reconstructions are presented and compared with film badge readings in published reports and SAIC memoranda. It also facilitates an identification of the kinds of exposure scenarios in which use of a 3X upper bound factor may not be adequate. We have not attempted to evaluate the adequacy of a 3X upper bound factor on the basis of aggregations of comparisons of reconstructed doses with film badge readings in two or more cases, even when different cases involved units that were exposed under similar conditions.

The general approach we have taken in this analysis is the following. We first compare the dose obtained by applying a 3X upper bound factor to the reconstructed whole-body dose for a particular unit, either the mean dose or a point estimate of dose with no reported uncertainty, in rem with film badge readings for members of that unit that are not adjusted to account for the bias in badge readings discussed in the previous section; badge readings are reported in rem. Such comparisons conform to the way reconstructed doses and badge readings are presented in unit dose reconstructions and to the policy of the NTPR Program noted in Section 1.1 that badge readings in R are assumed to give whole-body doses in rem. If use of a 3X upper bound factor is found to be adequate when a reconstructed dose is compared with unadjusted badge readings, that conclusion would not be affected if the bias in badge readings, which reduces the estimated dose to the whole body, were taken into account. Only when use of a 3X upper bound factor is found to be inadequate on the basis of a comparison of a reconstructed dose for a particular unit with unadjusted badge readings for members of that unit is the bias in badge readings taken into account in evaluating the adequacy of a 3X upper bound factor.[4]

[4] Biases in film badge readings are taken into account, as needed, only in cases of exposure to residual gamma radiation. Biases in badge readings are not considered in cases of exposure to initial gamma radiation (i.e., in cases of exposure of forward observers at NTS), because film badges that recorded exposures to initial gamma radiation often were not worn by participants and some of the biases that contribute to the overall bias factors in Table 1.1 (see footnote 3) either do not apply or are somewhat different than biases that apply to exposure to residual gamma radiation. As indicated by analyses in Sections 2 and 4–6, possible biases in film badge readings did not need to be considered in evaluating the adequacy of a 3X upper bound factor in cases of exposure to initial gamma radiation at NTS.

In comparing reconstructed doses with film badge readings when doses were low, the minimum dose that a film badge can distinguish from zero also is taken into account. The NRC (1989) report assigned a minimum detectable exposure of 40 mR to film badges at all operations. In this report, we have assumed a nominal minimum detectable dose of 50 mrem on the basis of a "threshold of reliability" that has been used in the NTPR Program (Barrett et al., 1987). When badge readings are below 50 mrem, comparisons with reconstructed doses that also are below 50 mrem are not considered to be meaningful.

### 1.5 Sources of Data Used in Analysis and Consideration of Data in NuTRIS

In the analysis presented in this report, film badge readings that are compared with reconstructed doses are obtained from published unit dose reconstructions or SAIC memoranda. Most published unit dose reconstructions are given in reports prepared by SAIC, although a few are given in other reports that include more general descriptions of all activities that took place at particular operations and tests.

Another source of information on film badge readings for participants is the NTPR Program's NuTRIS (Nuclear Test Review Information System) database. Throughout our analysis, we attempted to use badge readings given in NuTRIS, in addition to readings that were reported in published unit dose reconstructions or SAIC memoranda. However, this effort proved to be less informative than we hoped. The most important difficulty was that the badge readings in published unit dose reconstructions or SAIC memoranda frequently did not correspond well with readings for members of the same unit in NuTRIS; i.e., some reported badge readings were not given in NuTRIS or vice versa. Given these inconsistencies, we could not conclude that badge readings in NuTRIS that were not reported in published unit dose reconstructions or SAIC memoranda could be used reliably in our analysis.

Two other difficulties were encountered in attempting to compare film badge readings in NuTRIS with reconstructed doses for military units at PPG. The first was that NuTRIS does not distinguish between permanent badges and mission badges. This is an important concern when only permanent badges were relevant in comparisons with reconstructed doses. The second difficulty occurred in cases, such as on ships at Operation CASTLE, where readings of cohort film badges were assigned to unbadged participants. In those cases, NuTRIS does not indicate

which participants were badged and which were assigned a dose equal to a cohort badge reading. Thus, on the basis of information in NuTRIS, we were unsure of the total number of film badges on a ship and their readings, and there was uncertainty about the fraction of all badge readings that exceed a reconstructed mean dose by more than a factor of three.

Given these difficulties, we did not use badge readings obtained from NuTRIS in evaluating the adequacy of a 3X upper bound factor, although comparisons of reconstructed doses with badge readings in NuTRIS are presented in some cases, especially when badge readings were not reported in unit dose reconstructions and the number of badge readings in NuTRIS is substantial. However, NuTRIS did provide useful information. For example, we identified a few cases where reconstructed doses may have been assigned inappropriately to unbadged participants in particular units. In addition, information in NuTRIS gave no indication that there are additional types of exposure situations where use of a 3X upper bound factor is inadequate beyond situations we identified on the basis of reconstructed doses and film badge readings that were reported in published unit dose reconstructions or SAIC memoranda.

### 1.6 Organization of Report

The following sections present comparisons of reconstructed external gamma doses in published unit dose reconstructions and SAIC memoranda with relevant film badge readings at several operations at NTS or PPG. If an operation is not considered, either there are no unit dose reconstructions at that operation or there are no opportunities to compare reconstructed doses with film badge readings; this situation applies at Operations RANGER (1951), HARDTACK II (1958), and DOMINIC II (1962) at NTS. Exposures at the Trinity site in New Mexico and at Hiroshima or Nagasaki, Japan, in 1945 also are not considered, since all doses at the Trinity site have been estimated on the basis of film badge readings for participants or a suitable cohort (DTRA, 2008; Appendix C-1, Section 3.1) and film badges were not used in Japan. A final section summarizes the results of our analysis and presents some general conclusions from our evaluation of the adequacy of a generic 3X upper bound factor.

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# 2. OPERATIONS AT NTS – I.
# OPERATION BUSTER-JANGLE (1951)

## 2.1 Published Unit Dose Reconstructions

Dose reconstructions for military units at Operation BUSTER-JANGLE are given in a published report by Barrett et al. (1987).

### 2.1.1 *Initial Gamma Doses*

Readings of film badges that were placed at distances of 1700–4500 yards from ground zero at Shot DOG are compared with calculations of initial gamma dose in Figure 5 of Barrett et al. (1987). These badges were not worn by participants, but they should provide reasonable estimates of initial gamma dose that would have been received at those locations. There were no significant exposures to initial gamma radiation at this operation (Barrett et al., 1987).

At all but the closest distance from ground zero, the upper bound of the distribution of film badge readings (either unshielded badges in unprotected positions on the ground or equipment badges in positions where participants would have been exposed if they had been present) exceeds the calculated dose. At all distances, the upper bound of the distribution of badge readings and the calculated dose differ by about a factor of two or less. Thus, at all distances, use of a 3X upper bound factor gives upper bounds of reconstructed initial gamma doses that are at least upper 95% confidence limits.

More recent calculations of initial gamma doses at Shot DOG are given in Figure 29 of Santoro et al. (2005), which also compares calculated doses with central estimates of measured doses. At all distances from ground zero, measured doses exceed the calculated doses by a factor between 1.3 and 2. The more recent calculations do not affect the conclusion about the adequacy of a 3X upper bound factor on the basis of information reported by Barrett et al. (1987).

### 2.1.2 *Residual Gamma Doses*

Several comparisons of reconstructed doses from exposure to residual gamma radiation at locations near ground zero with film badge readings for participants in particular units are given by Barrett et al. (1987). In many cases, reconstructed doses were considered to be “high-sided” (i.e., upper bounds), and a mean dose was not estimated (Barrett et al., 1987).

**2.1.2.1** *Weapons Effects Evaluation Teams at Equipment Display Positions*. Members of weapons effects evaluation teams were exposed to residual gamma radiation from Shots CHARLIE (October 30) and DOG (November 1) at one of two equipment display positions. At Position 1, where about 25 individuals were exposed, high-sided reconstructed doses on three consecutive days are compared with film badge readings as follows:

October 30 –

- Reconstructed dose, 64 mrem
- Range of badge readings, 0–50 mrem
- Badge readings of zero, 14 of 20 total badges

October 31 –

- Reconstructed dose, 9 mrem
- Range of badge readings, 0–34 mrem
- Badge readings of zero, 9 of 17 total badges

November 1 –

- Reconstructed dose, 48 mrem
- Range of badge readings, 20–95 mrem (24 total badges)
- Mean badge reading, 45 mrem

The high-sided reconstructed dose exceeds all badge readings on the first day, but not on the second and third two days. Use of a 3X upper bound factor on the high-sided reconstructed doses gives upper bounds that exceed all badge readings on the first and third days, but not on

the second day. However, the comparison on the second day is not meaningful when all badge readings are below a nominal minimum detectable dose of 50 mrem (see Section 1.4).

At Position 2, where about 80 individuals were exposed, high-sided reconstructed doses are compared with film badge readings as follows:

October 30 –

- Reconstructed dose, 32 mrem
- Range of badge readings, 0–50 mrem
- Badge readings of zero, 18 of 27 total badges

October 31 –

- Reconstructed dose, 5 mrem
- Range of badge readings, 0–50 mrem
- Badge readings of zero, 9 of 16 total badges

November 1 –

- Reconstructed dose, 24 mrem
- Range of badge readings, 0–50 mrem and single reading of 95 mrem
- Badge readings of zero, 40 of 65 total badges

On all three days, the high-sided reconstructed dose is less than higher badge readings. On the first and third days, use of a 3X upper bound factor on the high-sided reconstructed doses gives upper bounds that exceed at least 95% of all badge readings. This is not the case on the second day. However, since all badge readings on that day are at or below a nominal minimum detectable dose of 50 mrem, this comparison is not meaningful.

**2.1.2.2** *Observers at Shot DOG*. About 2,800 observers at Shot DOG (November 1) were issued film badges. The high-sided reconstructed dose is compared with film badge readings as follows:

Reconstructed dose, 4 mrem

Range of badge readings, 0−320 mrem and single reading of 750 mrem

Badge readings of zero, 2,439 (87%)

Badge readings above nominal minimum detectable dose of 50 mrem, 37

The high-sided reconstructed dose, which is very low, is less than most non-zero film badge readings. By assuming that badge readings below a nominal minimum detectable dose of 50 mrem are not meaningful, use of a 3X upper bound factor on the high-sided reconstructed dose gives an upper bound dose (12 mrem) that is less than 37, or 1.3%, of the badge readings; i.e., the upper bound does not significantly underestimate doses to more than 95% of these observers.

Even though use of a 3X upper bound factor appears to be adequate when a minimum detectable dose is taken into account, the few badge readings that greatly exceed the high-sided reconstructed dose could be a concern. For example, nine badge readings exceed 100 mrem, or more than 15 times the reconstructed dose of 4 mrem when the bias of a factor of 1.5 in film badge readings at this operation (see Table 1.1) is taken into account. Barrett et al. (1987) states that the 37 badge readings above a nominal minimum detectable dose of 50 mrem "are likely due to the unauthorized [and documented] excursions of personnel who proceeded closer to ground zero than the remainder of the observer group" and that the highest badge reading of 750 mrem was "thought to be an equipment badge" (i.e., a badge that was placed close to ground zero prior to detonation and was exposed to initial gamma radiation). Regardless of the cause of the high badge readings in this case, however, the substantial number of readings that greatly exceed three times the high-sided reconstructed dose is not a significant concern, because the number of badges that were issued to observers at Shot DOG agrees with the total number of observers (Barrett et al., 1987). Therefore, there should be no need to use a reconstructed dose for unbadged observers that might greatly underestimate actual doses.[5]

[5] In a review of a previous draft of this report, SAIC analysts argued that the only reasonable explanation for the large discrepancies between the reconstructed dose and a few badge readings is that observers with high badge readings also participated in other, undocumented activities that were not taken into account in the dose reconstruction for observers; i.e., documented activities of observers could not have resulted in such high doses (Chehata, 2009). We do not dispute this view.

**2.1.2.3** *Maneuver Troops at Shot DOG*. In the dose reconstruction for maneuver troops at Shot DOG (November 1), a mean and upper bound of the external gamma dose were estimated.[6] The reconstructed mean dose is compared with 846 film badge readings as follows:

Reconstructed mean dose, 80 mrem

Range of badge readings, 0–200 mrem

Badge readings at or above 100 mrem, 12 (1.4%)

Use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all badge readings without accounting for the bias in badge readings.

**2.1.2.4** *Units at Shots SUGAR and UNCLE*. There are only a few reported film badge readings for participants who were exposed to residual gamma radiation from Shots SUGAR (November 19) and UNCLE (November 29). Reconstructed mean doses for different groups are compared with badge readings as follows:

Exposure of damage evaluators during pre-shot checks of equipment display positions at Shot UNCLE (exposure to fallout from Shot SUGAR) –

- Reconstructed mean dose, 0.19 rem
- Range of badge readings, 0.11–0.21 rem (6 total badges)

Exposure of senior Army officers during tour of equipment display positions eight days after Shot UNCLE –

- Reconstructed mean dose, 0.25 rem
- Range of badge readings, 0.12–0.19 rem (16 total badges)

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[6] Estimated upper bounds of reconstructed residual gamma doses to participants on the ground at NTS generally take into account uncertainties in external exposure rates at locations and times of exposure and uncertainties in locations of exposure and times spent at those locations. Scenario-specific upper bounds of doses given in unit dose reconstructions are not relevant to our evaluation of the adequacy of a 3X upper bound factor and are not given in this report.

Exposure of Exercise Desert Rock personnel during recovery of film packets from equipment display positions five days after Shot UNCLE –

- Reconstructed mean dose, 3.7 rem
- Range of badge readings, 4.65–5.80 rem (6 total badges)

In all three groups, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all badge readings without accounting for the bias in badge readings.

The few film badge readings at Shots SUGAR and UNCLE are representative only of unique activities by small groups of participants. There were no reported badge readings for a much larger number of participants that engaged in a variety of activities at Shot SUGAR or for most participants at Shot UNCLE. Reconstructed mean doses range from 1.4 to 2.7 rem for many groups at Shot SUGAR and from 0.5 to 3.7 rem for most participants at Shot UNCLE (Barrett et al., 1987; Table 14). Nonetheless, the agreement between the reconstructed mean dose and film badge readings in the small group at Shot UNCLE that received doses of about 5 rem provides support for the validity of dose reconstructions at higher doses at those shots.

**2.1.2.5** *Other Support Units*. Barrett et al. (1987) gives reconstructed doses for several support units at Shots DOG, SUGAR, and UNCLE. Film badge readings for members of those units were not reported, but badge readings are given in NuTRIS. In almost all units, most badge readings in NuTRIS are less than the reconstructed dose and are at or below a nominal minimum detectable dose of 50 mrem.

The one exception involves radiation-safety monitors, who were assigned a total reconstructed dose at Shots SUGAR and UNCLE of 1.08 rem (Barrett et al., 1987). Three of the seven monitors with badge readings in NuTRIS have total doses on the days of those shots of 1.65, 2.05, and 2.92 rem. The highest badge readings exceed the reconstructed dose by less than a factor of three without accounting for the bias in badge readings. However, it is questionable whether this comparison is meaningful when badge readings in NuTRIS were not reported in the published unit dose reconstruction.

## 2.2 SAIC Memoranda

Subsequent to publication of the unit dose reconstructions described in Section 2.1, several memoranda that addressed exposures of particular units were prepared by SAIC (Goetz, 1988; Klemm and Ortlieb, 1993; Ortlieb, 1996; Dancz, 2001). Only one of those memoranda gives a comparison of reconstructed external gamma doses with film badge readings.

Klemm and Ortlieb (1993) addressed exposure of members of an engineering support regiment in areas contaminated by fallout from Shot UNCLE at about 1–2 months after detonation. All badge readings are less than 0.3 rem. These readings are unexpectedly low when compared with the reconstructed mean dose of 1.4 rem for this unit during this period (Barrett et al., 1987; Table 14). Klemm and Ortlieb (1993) stated that the low badge readings may have applied to exposures during cleanup activities at outer, less contaminated positions near ground zero of Shot UNCLE. If this is the case, a comparison of the reconstructed dose in areas of higher contamination with film badge readings probably is not meaningful.

An earlier SAIC memorandum (McRaney and Weitz, 1984) addressed exposure of aircrews in Project 4.1 at Shots SUGAR and UNCLE. A reconstructed dose, but no film badge readings, is given. NuTRIS identifies three participants in Project 4.1 with film badge readings on the days of those shots. This number of badge readings is too few to allow a meaningful comparison with a reconstructed dose. Furthermore, the three participants with badge readings were not members of the service branch (Air Force) that provided aircrews for this project, and those participants also have badge readings in NuTRIS on days other than the days of Shots SUGAR and UNCLE, which may indicate that they were exposed in ways different from other members of aircrews. Therefore, the unit dose reconstruction, which considered exposure while airborne only, may not apply to those individuals.

Other SAIC memoranda that were prepared prior to publication of unit dose reconstructions by Barrett et al. (1987) are not considered in this analysis. Dose reconstructions in the earlier memoranda are considered to be superseded by those in the published report.

## 2.3 Summary of Analysis

Results of an analysis to compare reconstructed external gamma doses from exposures at Operation BUSTER-JANGLE given in published unit dose reconstructions with relevant film badge readings are summarized as follows:

- On the basis of comparisons at varying distances from ground zero at a single shot, use of a 3X upper bound factor appears to give upper bounds of reconstructed initial gamma doses that are at least upper 95% confidence limits.
- In cases of exposure to residual gamma radiation where a substantial fraction of film badge readings exceed a nominal minimum detectable dose of 50 mrem, use of a 3X upper bound factor on a reconstructed mean or high-sided dose gives upper bounds that exceed all badge readings.
- In cases of exposure to residual gamma radiation where most film badge readings are below a nominal minimum detectable dose of 50 mrem, no more than 1.3% of all badge readings exceed the nominal minimum detectable dose and exceed the reconstructed dose by more than a factor of three.

Therefore, in cases of exposure to residual gamma radiation, information in published unit dose reconstructions indicates that use of a 3X upper bound factor on a reconstructed dose, either a mean or a high-sided dose, gives upper bounds that are at least upper 95% confidence limits. Limited information in SAIC memoranda does not appear to allow meaningful comparisons of reconstructed doses with film badge readings in other cases.

A comparison of a high-sided reconstructed dose with film badge readings for observers at Shot DOG provides a case where a small percentage of badge readings above a nominal minimum detectable dose of 50 mrem are much higher than the reconstructed dose. By excluding a single reading of 750 mrem and accounting for the bias factor of 1.5 in badge readings at this operation, these few badge readings are a factor of about 15–50 higher than the high-sided reconstructed dose of 4 mrem. The most likely explanation for these large discrepancies is that the few high badge readings represent unauthorized exposures that were not taken into account in the dose reconstruction for observers. Furthermore, any concerns about reconstructed doses would be unimportant when all observers apparently have a badge reading.

Published unit dose reconstructions at this operation provide only limited opportunity to evaluate the adequacy of a 3X upper bound factor at higher residual gamma doses (e.g., doses above 1 rem) at Shots SUGAR and UNCLE.[7] Use of a 3X upper bound factor was found to be adequate in the limited number of cases at those shots where reconstructed doses could be compared with film badge readings. However, badge readings were not reported for several groups of participants with reconstructed mean doses above 1 rem.

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[7] In this report, a dose of 1 rem is used to distinguish between relatively high and relatively low doses. The choice of this dose is somewhat arbitrary, but a distinction between higher and lower doses is useful in evaluating the significance of comparisons of reconstructed doses with film badge readings.

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# 3. OPERATIONS AT NTS – II.
# OPERATION TUMBLER-SNAPPER (1952)

## 3.1 Published Unit Dose Reconstructions

Dose reconstructions for military units at Operation TUMBLER-SNAPPER are given in a published report by Goetz et al. (1985). All unit dose reconstructions are concerned with exposure to residual gamma radiation.

### 3.1.1 *Observers at Shot FOX*

There were 1,450 observers at Shot FOX (May 25), but only 104 film badge records were available. The reconstructed mean dose is compared with film badge readings as follows:

Reconstructed mean dose, 0.13 rem
Group of 10 badge readings – mean (upper bound), 0.11 (0.16) rem
Group of 88 badge readings – mean (upper bound), 0.30 (0.39) rem
Highest badge reading among 6 outliers, 0.84 rem

The upper bounds of badge readings in the two groups are 95th percentiles that we estimated from standard deviations of distributions of badge readings given by Goetz et al. (1985); individual badge readings or their distributions were not reported.[8]

In this case, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that is less than about 10, or 10%, of all badge readings.[9] To give an upper bound that exceeds at least 95% of all badge readings, an upper bound factor of about 4 would be required. However, when the unusually large bias of a factor of 2.1 in film badge readings at this operation (see Table 1.1) is taken into account, use of a 3X upper bound factor on the

[8] NuTRIS gives 81 film badge readings that presumably apply to observers at Shot FOX on the basis of their assignment on the day. Five badge readings are 0.47 rem or greater. This case provides an example of apparent discrepancies between film badge readings reported in published unit dose reconstructions and badge readings in NuTRIS (see Section 1.5).

[9] This estimate includes all six outliers and an assumption that four film badge readings in the group of 88 badges exceed the upper bound (95th percentile) of 0.39 rem.

reconstructed mean dose gives an upper bound that exceeds all but one (about 1%) of the badge readings. A limitation in evaluating the adequacy of a 3X upper bound factor in this case is the small number of badge readings, which may not be indicative of doses to all observers as a group, and the absence of badge readings for largest group of observers (Goetz et al., 1985).

Goetz et al. (1985) noted that the group of 88 higher badge readings for observers at Shot FOX may include doses that were received during undocumented activities at that shot. However, an analysis of activities and possible groupings of participants in relation to badge readings (JAYCOR, 1985) indicated that there was no evidence to support such an assumption, and that the most reasonable conclusion is that the reconstructed dose for all observers as a group is too low. NuTRIS indicates that the reconstructed mean dose of 0.13 rem has been assigned to unbadged observers at Shot FOX, in spite of the evidence from limited film badge readings that the reconstructed dose is too low. This discrepancy could be important when a whole-body dose in rem is assumed to be equal to a badge reading in R without accounting for the bias in badge readings (DTRA, 2008). Given the conclusion noted above that all film badge readings for observers are relevant, we believe that the mean of all badge readings should be assigned to unbadged observers at Shot FOX.

### 3.1.2 *Observers and Maneuver Troops at Shot GEORGE*

There were about 1,950 observers and maneuver troops at Shot GEORGE (June 1), but only 238 film badge records were available. The reconstructed mean dose is compared with badge readings as follows:

Reconstructed mean dose to maneuver troops, 0.11 rem
Reconstructed mean dose to observers, 0.028 rem
Mean (upper bound) of film badge readings, 0.16 (0.21) rem
Highest badge reading among 9 outliers, 0.30 rem

If all badge readings are assumed to apply to maneuver troops (DTRA, 2008; Appendix C-4, Sections 9.1.2 and 9.2.2), use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all badge readings. However, the few badge readings (12% of all participants) may not represent doses to all maneuver troops as a group, and available badge

readings may not all apply to maneuver troops. If some badge readings apply to observers, use of a 3X upper bound factor on the reconstructed mean dose for that group may not give an upper bound that exceeds at least 95% of all badge readings for observers. This could be the case even when the bias factor of 2.1 in badge readings is taken into account. If all higher badge readings apply to observers, which is an unlikely worst case, the required upper bound factor would be slightly greater than 3 (about 3.6). Thus, it seems unlikely that a 3X upper bound factor is inadequate in this case, and a possible inadequacy would not be substantial.

### **3.1.3** *Observers and Maneuver Troops at Shot DOG*

Goetz et al. (1985) gives a dose reconstruction for maneuver troops at Shot DOG (May 1); this dose reconstruction also applies to observers (DTRA, 2008; Appendix C-4, Section 6.1.3). The reconstructed mean dose given by Goetz et al. is 0.37 rem. In a subsequent revision of the dose reconstruction, however, the mean dose was increased to 0.67 rem (DTRA, 2008; Appendix C-4, Section 6.1.3). The basis for this increase was not documented.

Film badge readings for participants at Shot DOG were not reported by Goetz et al. (1985). However, an earlier report (Ponton and Maag, 1982; Section 5.3.1) indicates that badge readings for 25 maneuver troops are 1.5 rem or less.[10] If that information is valid, use of a 3X upper bound factor on the revised reconstructed mean dose of 0.67 rem gives an upper bound that exceeds the highest badge reading without accounting for the bias in badge readings.

## 3.2 SAIC Memoranda

Subsequent to publication of the unit dose reconstructions described in Section 3.1, a few memoranda that addressed exposures of particular units were prepared by SAIC (Ortlieb, 1985; Goetz, 1986; Klemm, 1994; Booker, 1995). None of those memoranda give a comparison of reconstructed external gamma doses with film badge readings.

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[10] Maneuver troops at Shot DOG were members of the 1st Marine Corps Provisional Atomic Exercise Brigade (Ponton and Maag, 1982). NuTRIS gives four film badge readings for members of this unit during periods that include the day of Shot DOG; these readings are 0.10, 0.11, 0.995, and 1.48 rem.

Other SAIC memoranda that addressed exposures of observers or maneuver troops and were prepared prior to publication of the unit dose reconstructions by Goetz et al. (1985) are not considered in this analysis. A later memorandum (Ortlieb, 1997) indicates that they were superseded by the published unit dose reconstructions.

### 3.3 Summary of Analysis

Two comparisons of reconstructed external gamma doses from exposures at Operation TUMBLER-SNAPPER with relevant film badge readings are provided in published unit dose reconstructions; information in SAIC memoranda does not provide additional comparisons. Both comparisons apply to exposures of observers or maneuver troops to residual gamma radiation. Results of these comparisons are summarized as follows:

- In the case of exposure of observers at Shot FOX, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that is at least an upper 95% confidence limit when the large bias factor of 2.1 in film badge readings at this operation is taken into account.
- In the case of exposure of observers and maneuver troops at Shot GEORGE, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all badge readings, provided the higher badge readings apply to maneuver troops and not to observers, for whom the reconstructed mean dose is about a factor of six lower.

In the case at Shot FOX, we also noted that the assignment of the reconstructed mean dose to unbadged observers, as indicated in NuTRIS, probably is inappropriate, and we recommend that the mean of all film badge readings should be assigned instead.

A possible difficulty in evaluating the validity of the two comparisons summarized above is that film badge readings were available for only a small fraction of all participants (about 7% at Shot FOX and 12% at Shot GEORGE). Therefore, available badge readings may not be representative of doses to entire groups of participants at the two shots. Another possible difficulty concerns the assumption that all higher badge readings at Shot GEORGE apply to maneuver troops (DTRA, 2008; Appendix C-4, Sections 9.1.2 and 9.2.2). If some of the higher badge readings apply to observers, use of a 3X upper bound factor on the reconstructed mean

dose for observers may not give an upper bound that exceeds at least 95% of all badge readings for that group when the large bias in badge readings is taken into account. However, it seems unlikely that all higher badge readings apply to observers, and the required upper bound factor would be only slightly greater than 3 even if that were the case.

An additional comparison of reconstructed external gamma doses with film badge readings was based on a revised dose reconstruction for observers and maneuver troops at Shot DOG (DTRA, 2008; Appendix C-4, Section 6.1.3) and information on film badge readings for maneuver troops at that shot reported by Ponton and Maag (1982). Use of a 3X upper bound factor on the revised reconstructed mean dose gives an upper bound that exceeds the highest badge reading without accounting for the bias in badge readings. However, a possible concern about the validity of this comparison is that film badge readings summarized by Ponton and Maag (1982) were not included in the later unit dose reconstruction (Goetz et al., 1985).

Film badge readings were not available for participants at Shot CHARLIE, which included about 500 observers and 1,525 maneuver troops (Goetz et al., 1985). However, an inability to test the adequacy of a 3X upper bound factor in this case should not be an important concern when reconstructed mean doses are less than 0.03 rem (Goetz et al., 1985).

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# 4. OPERATIONS AT NTS – III.
# OPERATION UPSHOT-KNOTHOLE (1953)

## 4.1 Published Unit Dose Reconstructions

Dose reconstructions for military units at Operation UPSHOT-KNOTHOLE are given in published reports by Goetz et al. (1981), Frank et al. (1982), and Edwards et al. (1985).

### 4.1.1 *Initial Gamma Doses*

Comparisons of calculated initial gamma doses with readings of film badges that were placed at varying distances from ground zero (but were not worn by participants) are given in Figure 3-3 (Shot ANNIE), 3-5 (Shot NANCY), 3-6 (Shot BADGER), 3-8 (Shot SIMON), 3-9 (Shot HARRY), and 3-10 (Shot GRABLE) of Goetz et al. (1981). At all distances at all shots, the calculated dose and film badge reading differ by less than a factor of two. Thus, in all cases, use of a 3X upper bound factor gives upper bounds of reconstructed initial gamma doses that exceed all badge readings.

Reconstructed gamma doses to volunteer observers at locations close to ground zero at Shot NANCY (March 24), Shot BADGER (April 18), and Shot SIMON (April 25) are given by Goetz et al. (1981). Reconstructed mean doses are compared with film badge readings for those observers as follows:

Shot NANCY (distance of 2500 yards) –

- Reconstructed mean dose, 0.64 rem
- Range of badge readings, 0.3–0.55 rem (9 volunteer observers)

Shot BADGER (distance of 2000 yards) –

- Reconstructed mean dose, 7.2 rem
- Range of badge readings, 4.1–9.6 rem (12 volunteer observers)

Shot SIMON (distance of 2000 yards) –

- Reconstructed mean dose, 13.6 rem
- Range of badge readings, 9.5–17.5 rem (8 volunteer observers)

At all three shots, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all badge readings.

At Shots BADGER and SIMON, reconstructed doses and film badge readings include significant contributions from residual gamma radiation; only at Shot NANCY was exposure of volunteer observers due almost entirely to initial gamma radiation (Goetz et al., 1981). The contributions from residual gamma radiation were about 45% at Shot BADGER and 30% at Shot SIMON (Goetz et al., 1981). Nonetheless, the agreement between the reconstructed mean doses and film badge readings at those two shots supports the validity of reconstructed initial gamma doses at NTS at doses of several rem or higher.

### **4.1.2** *Residual Gamma Doses*

Comparisons of reconstructed residual gamma doses with film badge readings for several groups of participants in maneuver units are given by Frank et al. (1982) and Edwards et al. (1985). However, except for the few volunteer observers whose doses are discussed above, film badge readings for approximately 4,650 observers at this operation were not available (Goetz et al., 1981). Reconstructed mean doses to those observers from exposure to residual gamma radiation, which occurred at seven shots, range from 0.04 rem at Shot GRABLE to 1.3 rem at Shots BADGER and HARRY (Goetz et al., 1981).

**4.1.2.1** *Marine Brigade at Shot BADGER*. Exposure of the 2nd Marine Corps Provisional Atomic Exercise Brigade was due almost entirely to residual gamma radiation from Shot BADGER (April 18) and occurred during maneuvers and a tour of the equipment display area at that shot (Frank et al., 1982). Reconstructed mean doses for different groups in this unit are compared with film badge readings as follows:

1st Battalion, 8th Marines, company with highest badge readings –

- Reconstructed mean dose, 4.7 rem
- Range of badge readings, 4.2–7.1 rem

2nd Battalion, 3rd Marines –

- Reconstructed mean dose, 2.9 rem (2.8 rem for Company E)
- Mean badge readings in four companies, 2.9–3.8 rem
- Highest badge readings in any company, about 5.2 rem (4 readings)

Brigade Headquarters Staff –

- Reconstructed mean dose, 3.7 rem
- Range of badge readings, 3–5.7 rem (8 total badges)

The following information also is relevant to these comparisons:

- In the 1st Battalion, 8th Marines, the number of badge readings per company is 4–6 and the total number of readings is 19. Ranges of badge readings in companies that did not have the highest readings are 1.0–3.29, 1.59–3.5, and 3.41–6.2 rem.
- In the 2nd Battalion, 3rd Marines, the number of badge readings per company is 6–12; the total number of readings in this battalion was not given. Mean badge readings in the other three companies, excluding the four readings of about 5.2 rem, are 3.8, 3.1, and 3.3 rem; ranges of badge readings were not given. The four highest badge readings of about 5.2 rem were judged likely to apply to damage evaluators at an equipment display who received additional exposure that was not considered in the dose reconstruction.
- In Brigade Headquarters Staff, the two highest badge readings of 5.7 rem were judged likely to apply to damage evaluators.

In all three groups, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all badge readings, including readings that could have applied to damage evaluators, without accounting for the small bias of a factor of 1.1 in film badge readings at this operation (see Table 1.1). Doses to all three groups were well above 1 rem.

Frank et al. (1982) also gives a reconstructed mean dose of 0.5 rem for members of helicopter crews in the brigade. Film badge readings were not available, but an after-action

report cited by Frank et al. assigned a dose of 1 rem to all members of this group. We could not determine the basis for this estimate.

**4.1.2.2** *Maneuver Troops at Shot NANCY*. More than 11,000 Army troops participated in maneuvers at this operation, but only 82 film badge readings were available (Edwards et al., 1985). A listing of badge readings and the affiliation of those participants indicated that these readings apply to members of Battalion Combat Team (BCT)-B at Shot NANCY (March 24). Reconstructed mean doses for forward and rear elements in this unit are compared with film badge readings, which were categorized into three groups, as follows:

Reconstructed mean dose for forward elements, 2.4 rem[11]
Reconstructed mean dose for rear elements, 1.1 rem
Mean (upper bound) of badge readings in high dose group, 2.2 (2.4) rem
Range of badge readings in intermediate dose group, 1.1–1.6 rem
Mean (upper bound) of badge readings in low dose group, 0.9 (1.0) rem

The high, intermediate, and low dose groups of badge readings were assumed to apply to personnel in forward, intermediate, and rear elements of BCT-B, respectively (Edwards et al., 1985); a reconstructed dose for the intermediate dose group separately was not given. Use of a 3X upper bound factor on the reconstructed mean dose for either element gives an upper bound that exceeds all badge readings in any dose group without accounting for the bias factor of 1.1 in badge readings. Doses to most personnel in BCT-B were greater than 1 rem.

Ten other units participated in maneuvers at five shots in this operation, including BCT-A at Shot NANCY (Edwards et al., 1985). Reconstructed mean doses from exposure to residual gamma radiation range from 0.04 rem for BCT-A at Shot GRABLE to 3.1 rem for BCT-A at Shot SIMON (Goetz et al., 1981). Again, however, film badge readings for members of these units were not available.

[11] Reconstructed mean dose was obtained from Table 5-1 of Edwards et al. (1985); this dose also is given in the *Standard Operating Procedures Manual* (DTRA, 2008; Appendix C-5, Section 4.2.3, Table 6). Mean dose given in Section 5.2.2 of Edwards et al. (1985) is 2.2 rem.

### 4.2 SAIC Memoranda

Several memoranda that addressed exposures of particular units that were not considered in the unit dose reconstructions discussed in Section 4.1 were prepared by SAIC (Frank, 1982a,b; Phillips, 1983a,b; Ortlieb, 1984, 1985, 1995a,b; Ortlieb and Klemm, 1987; Klemm and Ortlieb, 1988; Klemm, 1988). Only two of those memoranda give comparisons of reconstructed external gamma doses with film badge readings.

Phillips (1983a) addressed exposure of personnel in a unit that assisted in equipment evaluation and recovery activities in Project 3.21 at Shots ENCORE (May 8) and GRABLE (May 25); almost all the dose was received at the latter shot. The reconstructed dose for participation in all activities after Shot GRABLE, which took place over three days, is 3.79 rem. Film badge readings for 21 individuals who probably were involved in Project 3.21 include three readings less than 0.1 rem, 12 readings of 0.1–1.0 rem, and six readings of 1.0–3.0 rem (Phillips, 1983a). Use of a 3X upper bound factor on the reconstructed dose gives an upper bound that exceeds all badge readings without accounting for the bias in badge readings.

Ortlieb (1984) addressed exposure of personnel in a unit that conducted helicopter tests at eight shots. Reconstructed residual gamma doses were compared with film badge readings for two time periods: the first period included participation at Shots ANNIE (March 17), NANCY (March 24), DIXIE (April 6), RAY (April 11), and BADGER (April 18); the second period included participation at Shots SIMON (April 25), ENCORE (May 8), and HARRY (May 19). Some personnel participated at shots in both time periods. In addition to carrying out helicopter tests, one helicopter participated in Project 6.10 at Shot HARRY. Reconstructed doses are compared with film badge readings for 11 members of this unit as follows:

- During the first period, reconstructed doses at each shot range from 0.001 to 2.6 rem; by far the highest doses (0.9–2.6 rem) were calculated at Shot BADGER. Absent specific information on helicopter assignment and shot participation, a dose of 2.6 rem was assumed to be a reasonable high-sided estimate. Film badge readings for four members of this unit during this period are 0.05 (twice), 0.08, and 2.14 rem.
- During the second period, reconstructed doses at each shot range from 0.001 to 0.68 rem, except the reconstructed dose during participation in Project 6.10 at Shot HARRY is

1.6 rem. Absent specific information on helicopter assignment and shot participation, a dose of 1.6 rem was assumed to be a reasonable high-sided estimate. Film badge readings for three members of this unit during this period are 0.04, 0.26, and 0.35 rem.

- The sum of the high-sided reconstructed doses during the two time periods is 4.2 rem. Film badge readings for four participants who were assigned to this unit during both time periods are 0.05, 0.78, 1.68, and 4.51 rem.

In all three cases, use of a 3X upper bound factor on the high-sided reconstructed dose gives an upper bound that exceeds all badge readings without accounting for the bias in badge readings. However, it is difficult to compare reconstructed doses for participants who were assigned to particular helicopters at particular shots with available film badge readings when the helicopter assignment and shot participation for each member of this unit were not given.

For some units, reconstructed external gamma doses given in SAIC memoranda (Phillips, 1983b; Ortlieb, 1985; Ortlieb, 1995a,b) could be compared with limited film badge readings in NuTRIS. However, since only one or two badge readings are given in NuTRIS in each case, meaningful comparisons with reconstructed doses cannot be made.

### 4.3 Summary of Analysis

Results of an analysis to compare reconstructed external gamma doses from exposures at Operation UPSHOT-KNOTHOLE given in published unit dose reconstructions or SAIC memoranda with relevant film badge readings are summarized as follows:

- On the basis of comparisons at varying distances from ground zero at six shots and comparisons for volunteer observers at specific distances from ground zero at three shots, use of a 3X upper bound factor gives upper bounds of reconstructed initial gamma doses that are at least upper 95% confidence limits.
- In all cases where reconstructed residual gamma doses could be compared with a substantial number of film badge readings, use of a 3X upper bound factor on the reconstructed mean or, for one unit, high-sided dose gives an upper bound that exceeds all badge readings and, thus, is at least an upper 95% confidence limit.

A difficulty in evaluating the significance of the comparisons of reconstructed residual gamma doses with film badge readings at this operation is that comparisons could be made in only a limited number of cases.  Except for the few volunteer observers at three shots, badge readings for observers who were exposed to residual gamma radiation at seven shots were unavailable (Goetz et al., 1981), and except for members of one battalion combat team at one shot, badge readings for Army maneuver troops in ten units at five shots also were unavailable (Edwards et al., 1985).  This is a potentially important concern when reconstructed doses for some units are relatively high (above 1 rem).  However, the limited comparisons support the validity of dose reconstructions in cases of exposure to residual gamma radiation at this operation and the adequacy of a 3X upper bound factor when doses were above 1 rem.

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# 5. OPERATIONS AT NTS – IV.
# OPERATION TEAPOT (1955)

## 5.1 Published Unit Dose Reconstructions

Dose reconstructions for military units at Operation TEAPOT are given in published reports by Goetz et al. (1980), Edwards et al. (1983), and Goetz et al. (1984).

### 5.1.1 *Initial Gamma Doses*

Comparisons of calculated initial gamma doses with readings of film badges that were placed at varying distances from ground zero (but were not worn by participants) are given in Figure 3-2 (Shot MOTH), 3-4 (Shot TESLA), 3-5 (Shot TURK), 3-7 (Shot BEE), 3-8 (Shot APPLE I), and 3-9 (Shot APPLE II) of Goetz et al. (1980). At all distances at all shots, the calculated dose and film badge reading differ by less than a factor of two. Thus, in all cases, use of a 3X upper bound factor gives upper bounds of reconstructed initial gamma doses that exceed all badge readings.

Film badge readings for observers who were exposed to initial gamma radiation were not reported by Goetz et al. (1980). A later report (Ponton et al., 1981) indicates that the average badge reading for ten volunteer observers at a distance of 2600 yards from ground zero at Shot APPLE II (May 5) was 1.3 rem; a range of badge readings was not reported.[12] The reconstructed mean dose for these observers is 1.6 rem, and about 80% of the reconstructed dose was due to initial gamma radiation (Goetz et al., 1980). Although available information on badge readings is limited, use of a 3X upper bound factor on the reconstructed mean initial gamma dose should give an upper bound that exceeds all badge readings. This would not be the case only if at least one badge reading exceeds 4.8 rem.

Reconstructed initial gamma doses for observers at Shot MOTH (February 22) given by Goetz et al. (1980) could be compared with limited film badge readings for that day in NuTRIS;

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[12] Goetz et al. (1980) reported the same average badge reading and referenced an after-action report of the test manager. NuTRIS gives only three badge readings (1.45 rem and two readings of 1.6 rem) that presumably apply to volunteer observers at Shot APPLE II on the basis of the reconstructed neutron dose of 4.5 rem that was assigned to those participants (Goetz et al., 1980).

residual gamma doses were negligible. However, NuTRIS gives only four badge readings, and a comparison with the reconstructed dose probably is not meaningful even if those badge readings are valid.

### 5.1.2 *Residual Gamma Radiation*

A comparison of reconstructed residual gamma doses with film badge readings for personnel in a Marine brigade is given by Goetz et al. (1984). In addition, NuTRIS gives a substantial number of film badge readings that could apply to observers at some shots where reconstructed doses are given by Goetz et al. (1980). However, there are no film badge readings for approximately 1,000 members of Task Force RAZOR that can be compared with reconstructed residual gamma doses for that unit given by Edwards et al. (1983).

**5.1.2.1** *Marine Brigade at Shot BEE*. Exposure of the 3rd Marine Corps Provisional Atomic Exercise Brigade was due almost entirely to residual gamma radiation from Shot BEE (March 22) and occurred mainly during maneuvers and a tour of equipment displays (Goetz et al., 1984). Reconstructed mean doses for different groups are compared with film badge readings for 460 of the 1,843 members of this brigade as follows:

Reconstructed mean doses –

- Serials 1–4, 0.57 rem
- Serials 5 and 6, 0.59 rem
- Personnel from camp detachment, 0.85 rem

Badge readings –

- Range of mean badge readings in different groups, 0.035–0.42 rem
- Mean (upper bound) of badge readings in rifle companies, 0.41 (0.49) rem
- Highest badge reading among 7 outliers above 0.5 rem, 0.87 rem

The slightly higher reconstructed dose for Serials 5 and 6 is due to a small contribution of 0.02 rem from initial gamma radiation at Shot BEE; the reconstructed initial gamma dose for Serials 1–4 is zero. The particular units in the brigade that comprised Serials 1–6 are listed in

Table 1 of Goetz et al. (1984), and the average badge reading by group is given in Table 4 of that report. With the exception of the seven badge readings above 0.5 rem, the mean badge reading for members of rifle companies is the highest. Although it is not easy to associate various distributions of film badge readings given in Section 6 of Goetz et al. (1984) with exposures of particular groups, use of a 3X upper bound factor on the lowest reconstructed mean dose gives an upper bound that exceeds all badge readings without accounting for the small bias of a factor of 1.1 in film badge readings at this operation (see Table 1.1).

**5.1.2.2** *Observers at Various Shots*. Reconstructed residual gamma doses for observers at seven shots are given by Goetz et al. (1980); film badge readings for these observers were not reported in the unit dose reconstructions. Reconstructed mean doses range from about 1 mrem at Shot MOTH to 1.3 rem at Shot TURK.

NuTRIS gives film badge readings for observers at three shots. Reconstructed mean doses, excluding doses to volunteer observers at Shot APPLE II discussed in Section 5.1.1 but including relatively small contributions from initial gamma radiation at all three shots, are compared with film badge readings in NuTRIS for the day of those shots as follows:

Shot BEE (March 22) –

- Reconstructed mean dose, 0.85 rem
- Range of badge readings, 0.06–0.69 rem and single readings of 1.16 and 1.18 rem (45 total badges)

Shot ESS (March 23) –

- Reconstructed mean dose, 0.04 rem
- Range of badge readings, 0–0.08 rem (5 total badges)

Shot APPLE II (May 5) –

- Reconstructed mean dose, 0.40 rem
- Range of badge readings, 0.06–0.92 rem (18 total badges)

At all three shots, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all badge readings without accounting for the bias in badge readings.

However, the significance of the comparisons at those three shots is difficult to evaluate when Goetz et al. (1980) stated that "due to inadequate film badge dosimetry data …, no significant comparison of calculated dose with film badge doses is possible" and no badge readings were reported. Especially at Shots BEE and APPLE II, where a substantial number of badge readings on the days of those shots are given in NuTRIS, it is difficult to reconcile the data in NuTRIS with the absence of badge readings in the published unit dose reconstructions without knowing the reasons for the judgment by Goetz et al. (1980) that the badge data were inadequate.

Film badge readings for observers on the days of Shots TURK (March 7) and MET (April 15) also are given in NuTRIS. However, there is only a single badge reading on the day of Shot TURK and only three readings on the day of Shot MET. Thus, even if the badge readings are relevant, comparisons with reconstructed doses are not meaningful.[13]

### 5.2 SAIC Memoranda

Several memoranda that addressed exposures of particular units that were not considered in the unit dose reconstructions discussed in Section 5.1 were prepared by SAIC (Goetz, 1981; Frank, 1981a,b, 1982; Gminder, 1983; Phillips, 1983; Phillips and Ortlieb, 1984; Goetz et al., 1985; Goetz, 1986; Orlieb, 1986, 1991; Thomas, 1987). Only one of those memoranda (Goetz et al., 1985) gives additional information related to comparisons of reconstructed external gamma doses with film badge readings. However, since the available badge readings were used to reconstruct doses at a decontamination station, information in that memorandum cannot be used to compare badge readings with reconstructed doses that were not based on those readings.

For some units, reconstructed external gamma doses given in SAIC memoranda (Frank, 1981a; Frank, 1982; Phillips and Ortlieb, 1984) could be compared with limited film badge readings given in NuTRIS. However, there are only three or fewer badge readings in NuTRIS in each case, which precludes meaningful comparisons with reconstructed doses even if the badge readings in NuTRIS are relevant.

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[13] The relevance of the three film badge readings in NuTRIS on the day of Shot MET is particularly questionable when observers were located at a distance of more than 10,000 yards at the time of the shot and, thus, received no initial gamma dose, observers left the area shortly after detonation, and there was no contamination in the area during pre-shot equipment inspections (Goetz et al., 1980).

### 5.3 Summary of Analysis

Results of an analysis to compare reconstructed external gamma doses from exposures at Operation TEAPOT given in published unit dose reconstructions with relevant film badge readings are summarized as follows:

- On the basis of comparisons at varying distances from ground zero at six shots and a comparison for volunteer observers at a specific distance from ground zero at a single shot, use of a 3X upper bound factor gives upper bounds of reconstructed initial gamma doses that are at least upper 95% confidence limits.
- Reconstructed residual gamma doses could be compared with film badge readings that were reported in published unit dose reconstructions in only three cases, which involved exposure of different elements of a maneuver unit at Shot BEE. In all three elements, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all badge readings and, thus, is at least an upper 95% confidence limit.

We also noted that a substantial number of film badge readings in NuTRIS may apply to observers at Shots BEE and APPLE II, and that a lesser number of badge readings in NuTRIS may apply to observers at Shot ESS. However, since badge readings for observers were not reported in the published unit dose reconstructions (Goetz et al., 1980) on the grounds that the data were inadequate, it is difficult to conclude that a comparison of reconstructed doses with badge readings in NuTRIS is meaningful in those cases. Given the limited opportunities to compare reconstructed residual gamma doses with film badge readings at this operation on the basis of information in published unit dose reconstructions, an investigation into the validity of badge readings in NuTRIS for observers at the three shots noted above could be informative.

An additional limitation in comparing reconstructed doses with film badge readings at this operation is the lack of badge readings for members of Task Force RAZOR at Shot APPLE II (Edwards et al., 1983). Reconstructed mean doses for various elements of the task force, excluding observers, are about 0.8 rem or higher (Edwards et al., 1983; Table 5-1). Those doses were due mainly to exposure to residual gamma radiation; contributions from initial gamma radiation were less than 20%.

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# 6. OPERATIONS AT NTS – V. OPERATION PLUMBBOB (1957)

## 6.1 Published Unit Dose Reconstructions

Dose reconstructions for military units at Operation PLUMBBOB are given in published reports by Goetz et al. (1979a), Goetz et al. (1980), and Frank et al. (1981a).

### 6.1.1 *Initial Gamma Doses*

Comparisons of calculated initial gamma doses with readings of film badges or chemical dosimeters that were placed at varying distances from ground zero (but were not worn by participants) are given in Figure 10 (Shot DOPPLER) of Goetz et al. (1979a) and in Figure 3-2 (Shot PRISCILLA) and 3-4 (Shot HOOD) of Frank et al. (1981a). At all distances at all shots, the calculated dose and film badge or chemical dosimeter reading differ by less than a factor of two. Measured doses tend to be less than calculated doses, except in the comparisons with chemical dosimeter readings at Shot HOOD. Thus, in all cases, use of a 3X upper bound factor gives upper bounds of reconstructed initial gamma doses that exceed all film badge or chemical dosimeter readings.

Members of Task Force WARRIOR were exposed to initial gamma radiation at Shot DOPPLER (August 23). The reconstructed mean dose given by Goetz et al. (1979a) is 0.14 rem, whereas a mean initial gamma dose of 0.23 rem is given in the *Standard Operating Procedures Manual* (DTRA, 2008; Appendix C-7, Section 4.2).[14] Although film badge readings for members of the task force are available, those badge readings also include higher exposures to residual gamma radiation (see Section 6.1.2.1). Therefore, a reconstructed initial gamma dose cannot be compared with film badge readings in this case. There were no other significant exposures to initial gamma radiation at this operation (Goetz et al., 1979a; Goetz et al., 1980; Frank et al., 1981a).

[14] The basis for the increase in mean dose is not documented in the Procedures Manual.

### 6.1.2 *Residual Gamma Doses*

Comparisons of reconstructed residual gamma doses with film badge readings for participants are given in all three published unit dose reconstructions noted above.

**6.1.2.1** *Task Force WARRIOR*. Exposures of Task Force WARRIOR (Project 50.1) occurred before and after Shot SMOKY on August 31 (Goetz et al., 1979a). Most members of the task force were issued two film badges. The first badge was used during a period up to August 27 and recorded exposure to initial gamma radiation at Shot DOPPLER discussed in Section 6.1.1 and exposure to fallout from Shots BOLTZMANN, DIABLO, and KEPLER. The second badge was used from August 27 to September 2 and recorded exposure to fallout from Shots DIABLO, SHASTA, and SMOKY. Reconstructed mean doses during these two time periods are compared with film badge readings as follows:

Time period up to August 27 –

- Reconstructed mean dose to most participants, 0.47 rem
- Reconstructed mean dose to participants exposed in more contaminated areas in Shot DIABLO fallout field, 0.56 rem
- Range of 523 badge readings, 0–0.8 rem and single reading of 1.04 rem

Time period from August 27 to September 2 –

- Reconstructed mean dose to most participants, 0.13 rem
- Reconstructed mean dose to participants exposed in more contaminated areas in Shot SHASTA fallout field, 0.16 rem
- Additional reconstructed mean dose to unidentified subgroups during equipment recovery or inspection of defensive positions, 0.06 rem and 0.12 rem, respectively
- Range of 480 badge readings, 0–0.4 rem
- Range of 22 badge readings, 0.8–1.4 rem and single readings of 2.0 and 2.5 rem[15]

[15] NuTRIS gives a film badge reading of 2.74 rem for one participant in Project 50.1.

In the first time period, use of a 3X upper bound factor on the reconstructed mean dose to most participants gives an upper bound that exceeds all badge readings without accounting for the bias of a factor of 1.3 in film badge readings at this operation (see Table 1.1). In the second time period, use of a 3X upper bound factor on the reconstructed mean dose to most participants gives an upper bound that exceeds at least 95% of all badge readings in the group of 480 badges (Goetz et al., 1979a). If the highest badge readings in that group apply to participants who were exposed in more contaminated areas in the Shot SHASTA fallout field or during equipment recovery or inspection of defensive positions after Shot SMOKY, use of a 3X upper bound factor on a reconstructed mean dose gives an upper bound that exceeds all 480 badge readings.

In the second time period, however, use of a 3X upper bound factor on the highest reconstructed mean dose that could apply to any member of the task force (i.e., a mean dose of 0.34 rem, including exposure in more contaminated areas in the Shot SHASTA fallout field and during equipment recovery and inspection of defensive positions after Shot SMOKY) gives an upper bound that is less than about 70% of the badge readings in the smaller group of 22 higher readings. Although the smaller group includes less than 5% of all badge readings for the task force in the second time period, the clear separation of badge readings in the two groups suggests that exposure of some members of the task force was not represented adequately in the dose reconstruction for this time period. To equal or exceed at least 95% of all film badge readings in the smaller group of 22 badges, the reconstructed mean dose during the second time period would need to be increased by a factor of about 5–12 when the bias factor of 1.3 in badge readings is taken into account. The required upper bound factor depends on whether exposure occurred in more contaminated areas in the Shot SHASTA fallout field and during participation in equipment recovery or inspection of defensive positions after Shot SMOKY.

In evaluating film badge readings during the second time period, Goetz et al. (1979a) argued that members of the task force with higher readings in the group of 22 badges must have disobeyed orders, either deliberately or inadvertently, and proceeded toward ground zero of Shot SMOKY instead of one of the planned objectives, because exposure rates that were estimated by extrapolation of field survey data taken after Shot SMOKY were too low to give doses indicated by the badge readings and badge readings for other members of the task force who proceeded toward the planned objectives are much lower. However, an NRC committee concluded that a more likely explanation is that some airborne radionuclides were separated from the rapidly

rising fireball shortly after detonation and transported toward the location of one of the planned objectives, where unexpected exposure to fallout occurred (NRC, 2003). An important consideration in the NRC committee's argument was the absence of field survey data in the vicinity of the planned objectives. Exposure rates in those areas that were assumed in the dose reconstruction were based on extrapolation of measurements in other directions from ground zero of Shot SMOKY and a belief, which lacked support by measurements, that all airborne radionuclides traveled in directions away from the areas of the planned objectives.

**6.1.2.2** *Task Force BIG BANG*. Exposures of Task Force BIG BANG occurred before and after Shot GALILEO on September 2 (Goetz et al., 1980). Most exposures were due to fallout from Shot SMOKY and occurred after Shot GALILEO. Reconstructed mean doses are compared with film badge readings as follows:

Reconstructed mean dose –
- Earliest finishers at infiltration course, 1.1 rem
- Average finishers at infiltration course, 1.4 rem
- Latest finishers at infiltration course, officers, and monitors, 1.8 rem

Range of badge readings excluding readings less than 0.3 rem, 0.9–3.2 rem (about 110 total badges)

In addition, a badge reading for one of the test troops at the infiltration course exceeds 2.6 rem, whereas median badge readings for officers and radiation-safety monitors are 2.4 and 2.8 rem, respectively, and nine of the ten badge readings for monitors range from 2.5 to 3.2 rem. Use of a 3X upper bound factor on the appropriate reconstructed mean dose for test troops or officers and monitors gives an upper bound that exceeds all film badge readings for those groups without accounting for the bias in badge readings.

Film badge readings less than 0.3 rem (about 50 total badges) were assumed to apply to members of the task force who did not participate in activities at the infiltration course in the Shot SMOKY fallout field, because those readings could not be reconciled with survey data at locations of exposure and known times spent at those locations (Goetz et al., 1980). The reconstructed doses given above thus do not apply to those members.

**6.1.2.3** *Marine Brigade at Shots PRISCILLA and HOOD*. Exposures of the 4th Marine Corps Provisional Atomic Exercise Brigade were due mainly to residual gamma radiation from neutron-induced activity at Shots PRISCILLA (June 24) and HOOD (July 5) (Frank et al., 1981a). Reconstructed mean doses for different groups in this unit are compared with film badge readings as follows:

Brigade staff, viewed Shot PRISCILLA display –

- Reconstructed mean dose, 0.59 rem
- Range of badge readings, ~0.25–0.5 rem (11 total badges)

Brigade staff, viewed Shot HOOD display –

- Reconstructed mean dose, 0.75 rem
- Range of badge readings, ~0.9–1.2 rem (13 total badges)

Brigade staff, did not view Shot PRISCILLA or HOOD displays –

- Reconstructed mean dose, 0.14 rem
- Range of badge readings, 0–0.1 rem (41 total badges)

2nd Battalion, viewed Shot PRISCILLA and HOOD displays –

- Reconstructed mean dose, 1.0–1.1 rem
- Mean badge reading (excluding outlier), 0.84 rem (18 total badges)
- Highest (outlier) badge reading, 1.22 rem

2nd Battalion, viewed Shot PRISCILLA display only –

- Reconstructed mean dose, 0.46 rem
- Mean badge reading, 0.34 rem (7 total badges)

2nd Battalion, did not view Shot PRISCILLA display –

- Reconstructed mean dose, 0.58–0.66 rem
- Mean badge reading (excluding outlier), 0.47–0.55 rem (86 total badges)
- Highest (outlier) badge reading, 1.2 rem

Helicopter crews, viewed Shot PRISCILLA display –

- Reconstructed mean dose, 0.47 rem
- Range of badge readings (excluding outliers), 0.29–0.46 rem (20 total badges)
- Outlier badge readings, about 1 rem (8 total badges)

Helicopter crews, did not view Shot PRISCILLA display –

- Reconstructed mean dose, 0.02 rem
- Range of badge readings, < 0.2 rem

Radiation-safety monitors, viewed Shot PRISCILLA display –

- Reconstructed mean dose, 0.48 rem
- Range of badge readings, 0.018–2.4 rem (175 total badges)

The following information also is relevant to these comparisons:

- Ranges of reconstructed mean doses for two groups in the 2nd Battalion and the range of mean film badge readings for one group in that battalion reflect small differences in reconstructed doses and badge readings for different companies while viewing the display at Shot HOOD.
- Mean film badge readings for members of the 2nd Battalion who did not view the display at Shot PRISCILLA exclude three badge readings below 0.1 rem and four readings of about 0.2–0.3 rem, in addition to the outlier at 1.2 rem.
- Film badge readings of around 1 rem for eight members of helicopter crews that viewed the display at Shot PRISCILLA could not be explained on the basis of known activities in the brigade exercise and were attributed to additional undocumented activities.
- A reconstructed dose greater than 0.5 rem for some radiation-safety monitors not indicated above was attributed to additional undocumented activities. The basis for this higher dose was not described by Frank et al. (1981a).
- A badge reading of 7.2 rem not given above could be explained by the participant's mission as an equipment display officer, which required an extended presence in the Shot HOOD display area that was not taken into account in the unit dose reconstruction.

With three exceptions, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all film badge readings without accounting for the bias in badge readings. The most important exception involves radiation-safety monitors who viewed the display at Shot PRISCILLA. Distributions of badge readings for that group shown in Figure 6-1 of Frank et al. (1981a) indicate that about 30 of the 175 readings (about 17%) exceed three times the reconstructed mean dose of 0.48 rem. To exceed at least 95% of all badge readings, an upper bound factor of about 4 would be required. However, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds at least 95% of all badge readings when the bias factor of 1.3 in film badge readings is taken into account. We also note that a finding that a substantial number of badge readings exceed three times the reconstructed mean dose would not be an important concern if all radiation-safety monitors have badge readings, because there would be no need to reconstruct doses for unbadged monitors that might significantly underestimate actual doses.[16] The other two exceptions—the low reconstructed mean dose for members of helicopter crews who did not view the display at Shot PRISCILLA compared with the highest badge readings and the badge reading of 7.2 rem for a single participant—are of lesser importance, because doses to helicopter crews were low[17] and the badge reading of 7.2 rem applies to a documented and unusual exposure that was not taken into account in the unit dose reconstruction.

### 6.2 SAIC Memoranda

Subsequent to publication of the unit dose reconstructions described in Section 6.1, two SAIC memoranda that addressed exposures of particular units were prepared (Frank, 1982; McRaney and Weitz, 1983). However, neither of those memoranda gives a comparison of reconstructed external gamma doses with film badge readings. An SAIC memorandum that

[16] NuTRIS indicates that most radiation-safety monitors wore film badges. However, NuTRIS also gives a few reconstructed gamma doses for monitors. Reconstructed doses for the date of Shot PRISCILLA are 0.002 or 0.46 rem; reconstructed doses for the dates of Shots PRISCILLA and HOOD are 0.46, 0.48, or 0.58 rem; and a reconstructed dose for the date of Shot HOOD is 0.50 rem. These doses suggest that the unusually high badge readings for some monitors that were attributed to additional undocumented activities in the unit dose reconstruction (Frank et al., 1981a) have not been taken into account in reconstructing doses to unbadged monitors.

[17] Frank et al. (1981a) does not give a distribution of film badge readings less than 0.2 rem.

addressed exposure of Headquarters staff of the 4th Marine Corps Provisional Atomic Exercise Brigade at Shot HOOD (Frank et al., 1981b) and was prepared prior to publication of the dose reconstructions for that unit by Frank et al. (1981a) is not considered in this analysis, since it was superseded by the published report.

In two cases, reconstructed external gamma doses in SAIC memoranda can be compared with limited film badge readings given in NuTRIS. These comparisons are summarized below.

Frank (1982) addressed exposure of Army troop observers in Project 50.2 at Shot PRISCILLA. NuTRIS gives many film badge readings for Army personnel in that project during the time period around the day of that shot. Most badge readings are between 0.2 and 0.6 rem, and the highest reading is 0.67 rem.[18] The reconstructed dose for Army observers at Shot PRISCILLA of 0.46 rem (Frank, 1982) is the same as the reconstructed mean dose for members of the 2nd Battalion, 4th Marine Corps Provisional Atomic Exercise Brigade who viewed the display at that shot (see Section 6.1.2.3). The highest film badge reading exceeds the reconstructed dose by less than a factor of two without accounting for the bias in badge readings.

Goetz et al. (1979b) addressed exposure of five officer volunteers at ground zero at Shot JOHN (July 19), which was detonated at a high altitude. Film badge readings in NuTRIS for those volunteers are zero (three readings), 0.035, and 0.055 rem; all but one of these readings is below a nominal minimum detectable dose of 0.050 rem (see Section 1.4). The calculated initial gamma dose is 0.015 rem. The highest badge reading exceeds the calculated dose by more than a factor of three, but the two differ by less than a factor of three when the bias factor of 1.3 in badge readings is taken into account.

Film badge readings in NuTRIS in the two cases discussed above are not taken into account in evaluating the adequacy of a 3X upper bound factor in dose reconstructions at this operation. However, in the case of exposure of volunteer observers at Shot JOHN, film badge readings in NuTRIS support a conclusion that a 3X upper bound factor is adequate in all cases of exposure to initial gamma radiation.

[18] Badge readings during periods that extend well beyond the date of Shot PRISCILLA are as high as about 1.4 rem. These readings could have included exposure at later shots and were not considered in a comparison with the reconstructed dose.

### 6.3 Summary of Analysis

Results of an analysis to compare reconstructed external gamma doses from exposures at Operation PLUMBBOB given in published unit dose reconstructions or SAIC memoranda with relevant film badge readings are summarized as follows:

- On the basis of comparisons at varying distances from ground zero at three shots, use of a 3X upper bound factor gives upper bounds of reconstructed initial gamma doses that are at least upper 95% confidence limits.
- In 13 of the 14 cases of exposure to residual gamma radiation where doses were above a nominal minimum detectable dose of 50 mrem, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds at least 95% of all badge readings when the bias in film badge readings at this operation is taken into account.
- The one case where use of a 3X upper bound factor is not adequate involves exposure of members of Task Force WARRIOR during the period from August 27 to September 2, mainly to residual gamma radiation. Although use of a 3X upper bound factor on the lowest reconstructed mean dose for members of the task force gives an upper bound that exceeds at least 95% of all badge readings during that period, that upper bound is substantially less than badge readings in a group of 22 badges (about 4% of the total) with readings that were at least a factor of two higher than all other badge readings. When the bias in film badge readings at this operation is taken into account, an increase in reconstructed mean doses for members of that group by a factor of about 5–12 is required to give an upper bound that exceeds at least 95% of all badge readings in that group during that period. The required upper bound factor depends on the particular activities in which members of that group participated.

We also noted that the adequacy of a 3X upper bound factor in cases of exposure to initial gamma radiation is supported by a comparison of the reconstructed dose for five volunteer observers at Shot JOHN with film badge readings given in NuTRIS.

In an additional case involving exposure of helicopter crews that did not view the display at Shot PRISCILLA, the highest badge readings are about an order of magnitude higher than the reconstructed mean dose. However, a possible discrepancy in this case is not meaningful when

the reconstructed mean dose and most film badge readings are below a nominal minimum detectable dose of 50 mrem.

The large discrepancy between reconstructed mean doses and the higher readings in the small group of 22 film badges for members of Task Force WARRIOR probably is best explained by the absence of measured exposure rates near locations of exposure and the inappropriateness of extrapolating exposure rates at other locations in different directions from ground zero at Shot SMOKY, rather than an important deficiency in methods of dose reconstruction. To give an upper bound that is at least an upper 95% confidence limit in that group, the required upper bound factor depends on whether group members were exposed in more contaminated areas in the Shot SHASTA fallout field or participated in equipment recovery or inspection of defensive positions after Shot SMOKY. However, the substantial underestimation of doses to the small group in Task Force WARRIOR probably is unimportant when badge readings apparently are available for most members of the task force (Goetz et al., 1979a). Underestimation of doses would be a concern only if an unbadged participant were a member of the small group that received the highest doses and a reconstructed dose were assigned to that individual.[19]

Published unit dose reconstructions at this operation (Goetz et al., 1979a; Goetz et al., 1980; Frank et al., 1981) apparently address most exposures of observers and maneuver troops to residual gamma radiation; exceptions include observers at Shot DIABLO who toured a display area that was used at Shot HOOD and observers at Shot KEPPLER who experienced unexpected fallout prior to their evacuation (West et al., 1981; Maag and Ponton, 1981; Massie and Ponton, 1981). Thus, coverage of significant exposures by unit dose reconstructions and film badge readings is more complete at this operation than at earlier operations at NTS, which allows a more complete evaluation of the adequacy of a 3X upper bound factor. The lack of unit dose reconstructions for the two groups of observers may not be an important concern when observers at this operation were issued film badges (Harris et al., 1981).

[19] Information in NuTRIS indicates that very few participants in Project 50.1 have been assigned a reconstructed residual gamma dose, and that none of the assigned reconstructed doses apply to the time period from August 27 to September 2 only.

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# 7. OPERATIONS AT PPG – I.
# OPERATION CROSSROADS (1946)

## 7.1 Published Unit Dose Reconstructions

Dose reconstructions for military units at Operation CROSSROADS, which was conducted at Bikini Atoll, are given in published reports by Weitz et al. (1982a–c) and Berkhouse et al. (1984). Those dose reconstructions are concerned with exposure of naval units to residual gamma radiation on specific support or target ships.

Exposures on support or target ships occurred mainly during activities in Bikini Lagoon. The following sources of exposure during those activities were considered:

- Lagoon water that was contaminated by neutron activation products after Shot ABLE (July 1) and by fission products after Shot BAKER (July 25);
- Target ships that were contaminated by neutron activation products after Shot ABLE and by fission products that were deposited by the base surge after Shot BAKER;
- Fission products that accumulated on the hull and in salt-water piping and condensers/evaporators of support and target ships after Shot BAKER.

Exposures to contaminated target ships occurred while support ships were moored next to those ships and during temporary activities of boarding parties or permanent remanning of target ships.

On each target or support ship, daily doses from each source were reconstructed on the basis of ship-specific radiation survey data and modeling. Reconstructed daily doses during times spent at Bikini Atoll are given in tabular form for all support ships (Weitz et al., 1982c) and some target ships (Weitz et al., 1982b). Curves of shipboard gamma intensities (exposure rates) as a function of time after Shot BAKER are given for some target ships (Weitz et al., 1982b), and reference exposure rates on the day after Shot BAKER are tabulated for all target ships (DTRA, 2008; Appendix B-1, Table 5). These data can be used to reconstruct doses to members of boarding parties who did not wear film badges (DTRA, 2008; Appendix B-1, Section 5.1). In addition, a nomograph is provided for use in estimating external gamma doses to crew members on support ships and manned target ships due to accumulated contamination on the hull and in piping after those ships departed from Bikini Atoll (Weitz et al., 1982b,c).

Weitz et al. (1982a) compared reconstructed mean gamma doses for crew members on the support ship USS RECLAIMER who boarded target ships after Shot BAKER with film badge readings for those participants. These comparisons are summarized in Table 7.1. Except on August 2, boarding parties were assumed to be exposed only on the weather deck of a target ship, where exposure rates were the highest (Weitz et al., 1982b). The high badge readings compared with the reconstructed dose on August 13 were attributed to exposures of additional reported boarding parties on two target ships that could not be reconciled with records of the USS RECLAIMER's activities, which indicated that the RECLAIMER was not alongside either target ship on that date. Given this inconsistency and the lack of information on exposure times, these exposures were not taken into account in the dose reconstruction. On each day except August 13, when a comparison may not to be meaningful, use of a 3X upper bound factor on the reconstructed dose gives an upper bound that exceeds all badge readings without accounting for the bias of a factor of 1.5 in film badge readings at this operation (see Table 1.1).

**Table 7.1.** Comparisons of film badge readings with reconstructed doses for crew members on support ship USS RECLAIMER who served on boarding parties on target ships[a]

| Date | Number of badges | Range of badge readings (mrem) | Reconstructed dose (mrem) |
|---|---|---|---|
| July 31 | 5 | 50–50 | 85 |
| August 2 | 6 | 50–380 | 185 |
| August 5 | 1 | 300 | 229 |
| August 7 | 1 | 370 | 316 |
| August 8 | 3 | 100–230 | 187 |
| August 13 | 6 | 60–210 | 23 |
| August 17 | 2 | 60–60 | 82 |
| August 19 | 3 | 50–60 | 145 |

[a] See Weitz et al. (1982a), Section 5.

Berkhouse et al. (1984) compared reconstructed doses for members of boarding parties on the target ship USS INDEPENDENCE after Shot BAKER with film badge readings for those participants. These comparisons are summarized in Table 7.2. Reconstructed doses were based on measured exposure rates on the weather deck of that ship (Weitz et al., 1982b; Figure A-15)

and assumptions about the number of hours of exposure on each day. The high reconstructed doses compared with film badge readings were attributed to an assumption that all exposures occurred on the weather deck of the target ship, even though ship inspections required members of boarding parties to be below deck much of the time (Berkhouse et al., 1984). The exposure rate below deck on the USS INDEPENDENCE was about a factor of eight lower than on the weather deck (Weitz et al., 1982b; Figure A-15, and DTRA, 2008; Appendix B-1, Table 5).

**Table 7.2.** Comparisons of film badge readings with reconstructed doses for members of boarding parties on target ship USS INDEPENDENCE[a]

| Date | Number of badges | Average (maximum) badge reading (mrem) | Reconstructed dose (mrem) |
|---|---|---|---|
| August 18 | 32 | 44 (90) | 196 |
| August 19 | 44 | 48 (160) | 170 |
| August 20 | 42 | 33 (90) | 212 |
| August 21 | 35 | 52 (180) | 151 |

[a] See Berkhouse et al. (1984), Appendix G.

On all days, use of a 3X upper bound factor gives upper bounds of reconstructed doses on the USS INDEPENDENCE that exceed all film badge readings without accounting for the bias in badge readings. However, since reconstructed doses apparently were not based on realistic assumptions about the fraction of the time spent on the weather deck of the target ship, it is difficult to conclude with certainty that use of a 3X upper bound factor would give upper bounds of reconstructed doses that exceed all film badge readings if exposure below deck for a substantial fraction of the time were assumed in the dose reconstructions.[20]

NuTRIS was accessed to investigate whether film badge readings for participants on support or target ships could be compared with reconstructed doses tabulated by Weitz et al.

[20] Suppose, for example, that a member of an inspection team spent 75% of the time below deck, as assumed in dose reconstructions on target ships and for members of decontamination teams on target ships after August 12 (Phillips et al., 1985). By taking into account that the dose rate was a factor of about eight lower below deck, the total dose would be reduced by a factor of 0.25 + 0.75/8 = 0.34. If this reduction applies to boarding parties on the USS INDEPENDENCE, upper bounds of reconstructed doses that are obtained by use of a 3X upper bound factor would exceed all film badge readings on the first three days; this is also the case on the fourth day when the bias factor of 1.5 in film badge readings is taken into account.

(1982b,c). However, meaningful comparisons are difficult when activities associated with badge readings on particular dates are not described in NuTRIS and reconstructed daily doses on support ships (Weitz et al., 1982c) do not include exposures of boarding parties on target ships, which should be important when many badge readings probably include such exposures (Berkhouse et al., 1984). Doses to boarding parties on particular days could be estimated on the basis of curves of exposure rates over time on each target ship (Weitz et al., 1982b) and known activities and exposure times on ships. However, the latter information was not available to us.

### 7.2 SAIC Memoranda

Many memoranda that addressed exposures of particular units that were not considered in the unit dose reconstructions discussed in Section 7.1 or that present revisions of those dose reconstructions were prepared by SAIC (McRaney, 1981; Weitz, 1982, 1995, 1996a–d, 1997a,b, 1998, 1999; Thomas, 1984, 1986a,b, 1988, 1990, 1993a–c; Goetz, 1985, 1990; Dismukes and Thomas, 1990; Klemm and Thomas, 1992; Klemm, 1993, 1994). Some of those memoranda give additional information on comparisons of reconstructed external gamma doses with film badge readings. These comparisons are summarized below.

McRaney (1981) addressed exposure of crew members on photographic aircraft at Shot ABLE. All film badge readings for these participants are zero, and reconstructed doses for crew members on different aircraft range from 1 to 50 mrem.

Thomas (1986a) addressed exposure of boarding parties on three target ships. Maximum film badge readings for members of boarding parties on two of those ships, which also included exposures on a support ship, are compared with reconstructed doses as follows:

- On August 1, 2, and 3, maximum film badge readings for members of boarding parties on the USS MUGFORD are 0.12, 1.8, and 0.1 rem, and reconstructed doses are 0.437, 0.233, and 0.203 rem, respectively. The reconstructed dose on the first and third days exceeds the maximum film badge reading. This is not the case on the second day, when the high badge reading was marked as questionable.
- On August 9, 10, and 17, maximum film badge readings for members of boarding parties on the USS NEVADA are 0.14, 0.16, and 0.17 rem, and reconstructed doses are 0.607,

0.483, and 0.250 rem, respectively. The reconstructed dose exceeds the maximum film badge reading on each day.

Film badge readings for members of boarding parties on the USS STACK on August 3 and 4 were not reported by Thomas (1986a).

A subsequent analysis (Weitz, 1996c) addressed exposure of generic crewmen who participated in boarding parties on the USS NEVADA on August 9, 10, and 17. This dose reconstruction apparently is a revision of the dose reconstruction for boarding parties on this target ship by Thomas (1986a) discussed above.[21] The revised reconstructed doses on the three dates are 0.22, 0.16, and 0.06 rem, respectively. On all three days, use of a 3X upper bound factor on the revised reconstructed dose gives an upper bound that exceeds the maximum film badge reading reported by Thomas (1986a) without accounting for the bias in badge readings.

Weitz (1996d) addressed exposure of personnel who boarded the target ship USS SALT LAKE CITY after Shot BAKER. Averages of film badge readings on each day during the period August 4–8 were reported. The average badge readings and their ranges[22] are compared with reconstructed doses in Table 7.3. Except on August 7, use of a 3X upper bound factor on the reconstructed dose gives an upper bound that exceeds the highest film badge reading without accounting for the bias in badge readings. On August 7, use of a 3X upper bound factor gives an upper bound that exceeds the highest badge reading when the bias factor of 1.5 in film badge readings is taken into account.

Weitz (1997a) addressed exposure of crew members on the support ship USS O'BRIEN between July 1 and July 5. This ship received fallout from Shot ABLE while conducting downwind patrol operations. All film badges that were turned in on July 2 or July 5 read zero, and reconstructed doses for the two turn-in dates are 0.02 and 0.03 rem, respectively.

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[21] Weitz (1996c) indicates that reconstructed doses on August 9 and 10 that were obtained in a previous analysis, which was not cited, applied to members of inspection teams that remained on the target ship throughout the working day, and that the previous reconstructed dose on August 17 corresponded to the highest film badge reading on that date. The dose reconstruction by Weitz (1996c) was based on more realistic assumptions about exposure times for generic crew members on the target ship, and film badge readings were not used to reconstruct doses.

[22] Ranges of film badge readings on each date were obtained from a listing of individual readings used by Weitz (1996c), which was provided by SAIC (Chehata, 2009).

**Table 7.3.** Comparisons of film badge readings with reconstructed doses for members of boarding parties on target ship USS SALT LAKE CITY[a]

| Date | Number of badges | Badge readings (rem)[b] | Reconstructed dose (rem) |
|---|---|---|---|
| August 4 | 14 | 0.11 (0.07–0.19) | 0.18 |
| August 5 | 14 | 0.15 (0.05–0.32) | 0.17 |
| August 6 | 22 | 0.11 (0.05–0.23) | 0.14 |
| August 7 | 5 | 0.19 (0.04–0.40) | 0.12 |
| August 8 | 16 | 0.11 (0.05–0.21) | 0.13 |

[a] See Weitz (1996d).

[b] First entry for each day is average of all badge readings; entry in parentheses is range of badge readings provided by Chehata (2009).

In evaluating the significance of the comparisons summarized above, it is important to consider that film badge readings and reconstructed doses in some cases are at or below a nominal minimum detectable dose of 0.050 rem (see Section 1.4). Comparisons probably are not meaningful in those cases.

In a few cases, reconstructed external gamma doses in SAIC memoranda (Thomas, 1984; Klemm, 1994; Weitz, 1995, 1996a,b, 1997b) could be compared with film badge readings given in NuTRIS. However, since only three or fewer badge readings are given in NuTRIS in each case, meaningful comparisons with reconstructed doses cannot be made even if readings in NuTRIS apply to conditions of exposure that were considered in a dose reconstruction.

## 7.3 Summary of Analysis

Published unit dose reconstructions provide comparisons of reconstructed external gamma doses at Operation CROSSROADS with relevant film badge readings in only two cases, which involved exposure of crew members on the support ship USS RECLAIMER who served on boarding parties on target ships and exposure of members of boarding parties on the target ship USS INDEPENDENCE. With one exception, use of a 3X upper bound factor gives an upper bound of the reconstructed dose on a particular date that exceeds all film badge readings on that date. In the one exception out of 14 comparisons, which involved exposure of crew

members on the USS RECLAIMER, the highest badge reading exceeds the reconstructed dose by a factor of about 6 when the bias factor of 1.5 in film badge readings at this operation is taken into account. This discrepancy was attributed to additional boardings by crew members that could not be reconciled with records of the USS RECLAIMER's activities on that date and were not taken into account in the dose reconstruction.

We caution, however, that interpretation of the comparisons of reconstructed doses with film badge readings may not be unambiguous. Except for exposure of crew members on the USS RECLAIMER on a single date, all reconstructed doses were based on an assumption that exposure occurred only on the weather deck of a target ship, where exposure rates were higher than below deck. If badged participants spent most of the time below deck on a target ship, as may have occurred in boarding parties on the USS INDEPENDENCE (Berkhouse et al., 1984), it is possible that some film badge readings on a few more dates would exceed a reconstructed dose that is based on more realistic assumptions about times spent below deck by more than a factor of three, although this outcome appears unlikely when the bias factor of 1.5 in film badge readings is taken into account. Information that could be used to estimate exposure times of badged participants on the weather deck and below deck on target ships was not available to us. However, we also acknowledge that this should not be an important concern when reconstructed doses that were based on an assumption of exposure on the weather deck only are assigned to all unbadged participants. Another difficulty in evaluating the adequacy of a 3X upper bound factor is that there are three or fewer film badge readings for crew members on the USS RECLAIMER on some dates, and comparisons with reconstructed doses in those cases probably are not meaningful. Finally, the higher badge readings compared with the reconstructed dose for crew members on the USS RECLAIMER on one date remain unexplained.

SAIC memoranda also provide only limited comparisons of reconstructed doses with film badge readings. These comparisons are summarized below.

In cases of exposure on the target ship USS NEVADA, reconstructed doses on particular dates are higher than all film badge readings on those dates, except for exposure of generic crew members on one date. On all dates, use of a 3X upper bound factor gives an upper bound of the reconstructed dose that exceeds all badge readings. A possible difficulty in interpreting these comparisons is that the number of film badge readings on each date was not reported by Thomas

(1986a). If there were only a few badge readings, comparisons of reconstructed doses with those readings may not be meaningful.[23]

Reconstructed doses for members of boarding parties on two of the three dates on the target ship USS MUGFORD are higher than the maximum film badge readings on those dates. On the date when the maximum badge reading is much higher than the reconstructed dose, the high badge reading was marked as questionable. Since no other badge readings on that date were reported, the adequacy of a 3X upper bound factor in that case is unknown.

In cases of exposure of crew members on the target ship USS SALT LAKE CITY, use of a 3X upper bound factor gives upper bounds of reconstructed doses that exceed all film badge readings on all dates when the bias factor of 1.5 in badge readings at this operation is taken into account. Since there are a substantial number of badge readings on most dates, the comparisons on those dates should be meaningful.

Overall, on the basis of available information in published unit dose reconstructions and SAIC memoranda, the adequacy of a 3X upper bound factor in reconstructing external gamma doses at Operation CROSSROADS can be evaluated in only a limited number of cases. Furthermore, there often are only a few badge readings in cases where reconstructed doses can be compared with badge readings, which increases the difficulty in evaluating the adequacy of a 3X upper bound factor at this operation.

Two factors generally may limit an ability to make meaningful comparisons of reconstructed external gamma doses with film badge readings at this operation. First, it appears that, for the most part, doses have been reconstructed only for exposure situations where badge readings were not available, and there have not been extensive efforts to compare reconstructed doses with badge readings. Second, given that a daily exposure limit of 0.1 R was used at this operation (Berkhouse et al., 1984), most film badges were turned in within one day of their issuance. Since there apparently was little potential for high doses on most days and in most exposure situations, many comparisons involve doses at or below a nominal minimum detectable

[23] NuTRIS gives film badge readings on the USS NEVADA of 0.10, 0.12, and 0.14 rem on August 9, no badge readings on August 10, and badge readings of zero (many), 0.03 (three readings), and 0.08 rem (three readings) on August 17. Only on August 9 are the badge readings in NuTRIS consistent with the maximum readings reported by Thomas (1986a).

dose of 50 mrem, and there are few exposure situations where doses well above a minimum detectable dose have been compared with reconstructed doses.[24]

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[24] Film badge readings for participants in various groups are summarized by Berkhouse et al. (1984). Radiation-safety monitors had the highest exposures; in this group, 56% of readable badges indicate zero exposure, 14% exceed 0.1 R, and the highest total exposure of an individual monitor is 3.7 R. Other groups of interest include initial boarding teams, for which 54% of the badge readings are zero, 16% exceed 0.1 R, and the highest reading is 0.72 R, and crew members on support or target ships after Shot BAKER, for which 57% of the badge readings are zero and 10% exceed 0.1 R.

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## 8. OPERATIONS AT PPG – II.
## OPERATION SANDSTONE (1948)

### 8.1 Published Unit Dose Reconstructions

Dose reconstructions for military units at Operation SANDSTONE, which was conducted at Enewetak Atoll, are given in a published report by Thomas et al. (1983). Those dose reconstructions are concerned with exposure of naval units on ships and on residence islands at Enewetak and Kwajalein Atolls to residual gamma radiation due to secondary (late-time) fallout from the three shots at this operation (Shot X-RAY on April 15, Shot YOKE on May 1, and Shot ZEBRA on May 15).

Reconstructed mean cumulative doses through May 31 (16 days after the last shot at this operation) are 57 and 84 mrem on Enewetak and Kwajalein Atoll, respectively, and range from 3 to 49 mrem on 31 ships. These doses were estimated by integrating measured exposure rates over time and taking into account the shielding provided by a ship's structure when participants were below deck or by buildings when participants on land were indoors.

Thomas et al. (1983) compared reconstructed doses for typical crew members on ships and participants on residence islands with readings of film badges that recorded exposures over short time periods around the date of each shot. These comparisons are summarized as follows:

Exposure on ships (17 cases) –

- Number of badge readings on each ship, 1–20
- Range of average badge readings, 0–31 mrem (maximum reading of 60 mrem)
- Range of reconstructed doses, 1–14 mrem

Exposure on residence islands at Enewetak and Kwajalein Atolls (4 cases) –

- Number of badge readings at each atoll, 3 or 6
- Range of average badge readings, 0–10 mrem
- Range of reconstructed doses, 2–9 mrem

In the comparisons on ships, the largest discrepancies between an average film badge reading and a reconstructed dose include an average badge reading of 31 mrem and a reconstructed dose

of 2 mrem on the USS BAIROKO at the time of Shot ZEBRA, an average badge reading of 30 mrem and a reconstructed dose of 1 mrem on the USS PICKAWAY at the time of Shot YOKE, and an average badge reading of 26 mrem and a reconstructed dose of 1 mrem on the USS PICKAWAY at the time of Shot XRAY. However, when a nominal minimum detectable dose of 50 mrem (see Section 1.4) is taken into account, these discrepancies probably are not meaningful. Only three badge readings included in the comparisons by Thomas et al. (1983), two on the USS BAIROKO and one on the USS PICKAWAY, are at or above 50 mrem and, as noted above, the highest badge reading is only 60 mrem.

NuTRIS was accessed to investigate whether there are additional film badge readings that could be compared with reconstructed doses given by Thomas et al. (1983). During time periods when participants were assigned to units on Enewetak or Kwajalein Atoll or to particular ships, most badge readings do not exceed a nominal minimum detectable dose of 50 mrem and, thus, are in agreement with the low reconstructed doses. However, there are several cases involving a total of about 105 participants where one or more badge readings exceed a reconstructed dose by more than a factor of three. These cases are summarized as follows:

- About 80% of the participants on Enewetak or Kwajalein Atoll with unusually high badge readings in NuTRIS were radiation-safety monitors or members of drone or photography units. Those units included all island-based personnel with badge readings above 1 rem, and the highest reading is 4.5 rem. Other island-based personnel with high badge readings were members of engineer units, a Navy patrol squadron, an amphibious truck detachment, a detachment from the Army Counter-Intelligence Corps, a provisional military policy company, an Air Force base unit, a Naval air station ship security detail, a headquarters and service unit, and an inter-island transport unit. All film badge readings for members of those units are about 0.84 rem or less.
- About 80% of the participants on ships with unusually high badge readings in NuTRIS were assigned to the USS BAIROKO. Other ship-based personnel with high badge readings were assigned to the USS CURTISS or USS MARSH. Most badge readings for ship-based personnel are about 0.5 rem or less, except badge readings for four participants on the USS BAIROKO are between 1.3 and 6.0 rem.

It is highly unlikely that the unusually high film badge readings summarized above indicate important discrepancies with reconstructed doses given by Thomas et al. (1983). Most, if not all, of the high badge readings probably represent unusual exposure conditions that did not apply to most island- or ship-based personnel who were exposed only to fallout (DTRA, 2008; Appendix B-2, Section 4). This clearly is the case for radiation-safety monitors and members of drone or photography units, and it probably is also the case for members of island-based units that engaged in security or transport activities. The high badge readings for a substantial number of participants on the USS BAIROKO probably represent exposure to a radium source that was used to calibrate survey instruments (DTRA, 2008; Appendix B-2, Section 4.10), and the few higher badge readings (four readings of about 0.15 rem and one reading of 0.37 rem) for personnel on the USS CURTISS may have been due to persistent localized contamination by fallout (DTRA, 2008; Appendix B-2, Section 4.4). Measured exposure rates on ships and the two atolls (Thomas et al., 1983, and DTRA, 2007; Appendix B-2, Section 2.2) are too low to explain the unusually high film badge readings.

### 8.2 SAIC Memoranda

Several memoranda that addressed exposures of particular units that were not considered in the unit dose reconstructions discussed in Section 8.1 were prepared by SAIC (Gminder, 1981; Goetz, 1989; Martinez, 1995, 1998a–f; SAIC, 1996; Weitz, 1996; Orlieb, 1998; Booker, 2002). None of those memoranda give information on comparisons of reconstructed external gamma doses with film badge readings. Another memorandum (Klemm, 1996) reiterated the generic reconstructed dose of 0.06 rem for participants based on Enewetak Atoll that was calculated by Thomas et al. (1983) and discussed in Section 8.1.

### 8.3 Summary of Analysis

Published unit dose reconstructions provide comparisons of reconstructed doses from external exposure to residual gamma radiation at Operation SANDSTONE with relevant film badge readings only in cases of exposure to fallout on ships and residence islands where measured exposure rates were low. SAIC memoranda do not provide additional comparisons.

All reconstructed doses on ships are below a nominal minimum detectable dose of 50 mrem, and reconstructed doses on Enewetak and Kwajalein Atolls are only marginally greater than 50 mrem. Most relevant film badge readings also are less than 50 mrem and, thus, are consistent with reconstructed mean doses. Although a substantial number of unusually high badge readings for participants on the two atolls and on three ships are given in NuTRIS, most of the large discrepancies with reconstructed doses can be explained by the unusual activities of participants with those badge readings in high-radiation areas that were not taken into account in dose reconstructions. These discrepancies probably do not indicate that the published unit dose reconstructions are flawed.

At this operation, unit dose reconstructions in published reports and SAIC memoranda do not provide an opportunity to evaluate the adequacy of a 3X upper bound factor at higher residual gamma doses. In exposure situations where there was the potential for unusually high doses, the NTPR Program relies on a participant's statements and film badge readings for the participant or a member of the participant's exposure cohort to estimate external gamma dose (DTRA, 2008; Appendix B-2; Section 4). This approach should not lead to substantial underestimates of a participant's external gamma dose as long as relevant film badge readings are available, given that film badges generally were issued to at least some participants in situations with the potential for higher doses (Berkhouse et al., 1983).

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## 9. OPERATIONS AT PPG – III.
## OPERATION GREENHOUSE (1951)

### 9.1 Published Unit Dose Reconstructions

Dose reconstructions for military units at Operation GREENHOUSE, which was conducted at Enewetak Atoll, are given in published reports by Thomas et al. (1982) and Thomas et al. (1987). The first report addressed exposures on ships and on residence islands at Enewetak Atoll to residual gamma radiation due mainly to fallout from shots at this operation,[25] and the second report addressed exposures on residence islands during the post-operation period. In addition, Berkhouse et al. (1983) provided information on exposures of radiation-safety monitors on two residence islands following one of the shots at this operation.

#### 9.1.1 *Exposures During Operation*

Thomas et al. (1982) presented dose reconstructions for participants on seven ships and on three residence islands at Enewetak Atoll (Enewetak, Parry, and Japtan Island). The end date of calculations on the ships ranges from May 31 (the day Operation GREENHOUSE ended) to the end of October.[26] Daily doses on residence islands were calculated from April 8 (the day of Shot DOG) through May 31.[27] Fallout from three shots (DOG, EASY, and ITEM) contributed to doses on the ships and residence islands, but fallout from Shot GEORGE (May 9) did not. Doses due to fallout from Shot ITEM were the highest on the residence islands and most ships. Dose reconstructions by Thomas et al. (1982) apply only to ships' crews and to personnel that were assigned to the residence islands at Enewetak Atoll; they do not apply to participants in a

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[25] Exceptions occurred on the USS SPROSTON, where external gamma doses at Shot EASY apparently were due to the passing atmospheric cloud, rather than fallout on the ship, and external doses on the day of Shot ITEM also appear to be due mainly to the passing cloud (Thomas et al., 1982).

[26] Calculations on ships were carried out until the monthly dose due to fallout from all shots combined decreased below 30 mrem (Thomas et al., 1982).

[27] Calculations on residence islands were terminated on May 31 on the basis of contemporaneous reports which indicated that heavy rains had washed away most of the radioactive material. However, those reports were later found to be unsubstantiated, and dose reconstructions on residence islands discussed in Section 9.1.2 were carried out beyond May 31 (Thomas et al., 1987).

small boat pool, which operated from the USS CABILDO, or to aircrews stationed at Kwajalein Atoll.

**9.1.1.1** *Exposures on Ships*. This section presents comparisons of reconstructed residual gamma doses on ships with film badge readings for participants on those ships.

**9.1.1.1.1** *Comparisons in unit dose reconstructions*. Comparisons of reconstructed residual gamma doses with film badge readings on six ships presented by Thomas et al. (1982) are summarized as follows:[28]

Shot DOG (April 8) –

- USS CABILDO (April 8–13) –
  - Reconstructed mean dose, 0.060 rem
  - Range of badge readings, 0–0.58 rem (15 total badges)
- USS CURTISS (April 7–10) –
  - Reconstructed mean dose, 0.136 rem
  - Range of badge readings, 0.11–0.42 rem (17 total badges)
- USS LST-859 (April 7–13) –
  - Reconstructed mean dose, 0.209 rem
  - Range of badge readings, 0–0.40 rem (6 total badges)
- USNS SGT. CHARLES E. MOWER (April 7–16) –
  - Reconstructed mean dose, 0.137 rem
  - Range of badge readings, 0–0.17 rem (7 total badges)
- USS SPROSTON (April 8–15) –
  - Reconstructed mean dose, 0.072 rem
  - Range of badge readings, 0–0.11 rem (8 total badges)
- USS WALKER (April 8–14) –
  - Reconstructed mean dose, 0.056 rem
  - Range of badge readings, 0–0.18 rem (9 total badges)

[28] Reconstructed mean doses are tabulated values; film badge readings, which were not tabulated by Thomas et al. (1982), are estimated from Figures 5-1, 5-2, and 5-4 of that report.

Shot EASY (April 21) –

- USS CABILDO (April 20–27) –
  - Reconstructed mean dose, 0.024 rem
  - Range of badge readings, 0–0.065 rem (14 total badges)
- USS CURTISS (April 21–26) –
  - Reconstructed mean dose, 0.033 rem
  - Range of badge readings, 0.02–0.28 rem (18 total badges)
- USS LST-859 (April 20–25) –
  - Reconstructed mean dose, 0.025 rem
  - Range of badge readings, 0–0.095 rem (6 total badges)
- USNS SGT. CHARLES E. MOWER (April 21–27) –
  - Reconstructed mean dose, 0.021 rem
  - Range of badge readings, 0–0.095 rem (7 total badges)
- USS SPROSTON (April 19–27) –
  - Reconstructed mean dose, 0.093 rem
  - Range of badge readings, 0–0.38 rem (8 total badges)

Shot ITEM (May 25) –

- USS CABILDO (May 24–28) –
  - Reconstructed mean dose, 0.15 rem
  - Range of badge readings, 0.32–2.0 rem (16 total badges)
- USS CURTISS (May 25–26) –
  - Reconstructed mean dose, 0.128 rem
  - Range of badge readings, 0–0.28 rem (19 total badges)
- USNS SGT. CHARLES E. MOWER (May 24–27) –
  - Reconstructed mean dose, 0.35 rem
  - Range of badge readings, 0.31–2.2 rem (7 total badges)
- USS SPROSTON (May 24–25) –
  - Reconstructed mean dose, 0.001 rem
  - Range of badge readings, 0.08–0.18 rem (8 total badges)

No film badge readings were reported for personnel on the USNS LT. ROBERT CRAIG at Shot DOG or the USS WALKER at Shots EASY and ITEM, and the USNS CRAIG was not present at other shots. The USS LST-859 was away from Enewetak Atoll at the time of Shot ITEM, and four badge readings during the period May 25–28 are zero.

At the time of Shot GEORGE (May 9), all reconstructed mean doses due to fallout from Shots DOG and EASY are 10 mrem or less (Thomas et al., 1982). Reported film badge readings include 13 zeros on the USS CABILDO, 17 zeros on the USS CURTISS, six zeros and one reading of 0.28 rem on the USNS SGT. CHARLES E. MOWER, eight zeros on the USS SPROSTON, and 15 zeros and readings of 0.04 and 0.08 rem on the USS WALKER.

In several comparisons summarized above where most film badge readings are at or above a nominal minimum detectable dose of 0.050 rem (see Section 1.4), use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that is less than a substantial number of badge readings without accounting for the bias of a factor of 1.4 in film badge readings at this operation (see Table 1.1). Badge readings that exceed the reconstructed mean dose by more than a factor of three in these cases are summarized as follows:

- USS CABILDO at Shot DOG – five of 15 badge readings, with highest badge reading a factor of about 10 higher than reconstructed mean dose of 0.06 rem;
- USS CURTISS at Shot EASY – nine of 18 badge readings, with highest badge reading a factor of about 8 higher than reconstructed mean dose of 0.033 rem;
- USNS SGT. CHARLES E. MOWER at Shot EASY – three of seven badge readings, with highest badge reading a factor of about 5 higher than reconstructed mean dose of 0.021 rem;
- USS CABILDO at Shot ITEM – 12 of 16 badge readings, with highest badge reading a factor of about 13 higher than reconstructed mean dose of 0.15 rem;
- USNS SGT. CHARLES E. MOWER at Shot ITEM – two of seven badge readings, with highest badge reading a factor of about 6 higher than reconstructed mean dose of 0.35 rem;
- USS SPROSTON at Shot ITEM – all eight badge readings are about two orders of magnitude higher than reconstructed mean dose of 0.001 rem.

In addition, badge readings at Shot GEORGE of 0.28 rem on the USNS MOWER and 0.04 and 0.08 rem on the USS WALKER are more than an order of magnitude higher than the reconstructed mean doses of 0.0054 and 0.0032 rem, respectively.

When the bias factor of 1.4 in film badge readings at this operation is taken into account, adjusted badge readings that exceed the reconstructed mean dose by more than a factor of three in the six cases at Shots DOG, EASY, and ITEM listed above are summarized as follows:

- USS CABILDO at Shot DOG – four of 15 adjusted badge readings, with highest adjusted badge reading a factor of about 7 higher than reconstructed mean dose of 0.06 rem;
- USS CURTISS at Shot EASY – two of 18 adjusted badge readings, with highest adjusted badge reading a factor of about 6 higher than reconstructed mean dose of 0.033 rem;
- USNS SGT. CHARLES E. MOWER at Shot EASY – one of seven adjusted badge readings is a factor of about 3.2 higher than reconstructed mean dose of 0.021 rem;
- USS CABILDO at Shot ITEM – eight of 16 adjusted badge readings, with highest adjusted badge reading a factor of about 10 higher than reconstructed mean dose of 0.15 rem;
- USNS SGT. CHARLES E. MOWER at Shot ITEM – two of seven adjusted badge readings, with highest adjusted badge reading a factor of about 4.5 higher than reconstructed mean dose of 0.35 rem;
- USS SPROSTON at Shot ITEM – all eight adjusted badge readings are a factor of about 60–130 higher than reconstructed mean dose of 0.001 rem.

In addition, adjusted badge readings at Shot GEORGE of 0.20 rem on the USNS MOWER and 0.03 and 0.06 rem on the USS WALKER are at least an order of magnitude higher than the reconstructed mean doses.

In three cases listed above, exposure rates on a ship were not reported but were assumed to be determined by measurements on a nearby ship or residence island: exposure rates on the USS CURTISS and USNS MOWER at Shot EASY were assumed to be determined by measurements on Parry Island, and exposure rates on the USNS MOWER at Shot ITEM were assumed to be the same as on the USS CABILDO (Thomas et al., 1982). Exposure rates on the USS CABILDO and LST-859 at Shot EASY also were assumed to be determined by measurements on Parry Island, but there is good agreement between the reconstructed dose and

film badge readings in those two cases, in contrast to the comparisons on the USS CURTISS and USNS MOWER at that shot. Thus, the presence or absence of measured exposure rates on a ship does not appear to be the most important factor in determining whether the highest adjusted film badge readings exceed reconstructed doses by more than a factor of three.

Thomas et al. (1982) noted that reconstructed mean doses tend to systematically underestimate average film badge readings, as indicated in the comparisons summarized above. This tendency was explained, at least in part, by the duties of virtually all badged participants, which required them to be on the weather deck for a greater fraction of the day than was assumed in dose reconstructions that were intended to apply to average crew members. Thomas et al. (1982) also noted that most badged participants, including radiation-safety monitors and damage control and repair parties, probably were required to be on deck during periods of fallout, when an average crew member was assumed to be below deck, and that doses to badged participants during periods of fallout could have been about 50–60% of the daily dose assuming exposure on deck for 24 hours. For example, by assuming that the dose to more highly exposed personnel on the day fallout occurred was 60% of the dose assuming exposure on the weather deck for 24 hours and that the dose on other days was 20% higher than the reconstructed dose for an average crew member due to the increased time spent on deck, Thomas et al. (1982) estimated that the mean dose to more highly exposed personnel on the USS CURTISS at Shot DOG (April 7–10) was a factor of about 1.4 higher than the reconstructed mean dose for an average crew member. When likely conditions of higher exposure of badged participants were taken into account, Thomas et al. (1982) judged that there was generally good agreement between average film badge readings and reconstructed mean doses.

**9.1.1.1.2** *Comparisons based on more likely exposures of badged participants*. In the six cases discussed in the previous section where substantial discrepancies between reconstructed doses and film badge readings were found and most badge readings are at or above a nominal minimum detectable dose of 0.050 rem, we considered the effect of increasing reconstructed doses as in the analysis of higher exposures on the USS CURTISS at Shot DOG by Thomas et al. (1982). If we assume that the dose to badged participants on shot day was 60% of the dose assuming exposure on the weather deck for 24 hours and that the dose to badged participants on subsequent days was 20% higher than the reconstructed dose for an average crew member, the

increased reconstructed mean doses that we calculated from mean daily exposures on deck and mean daily doses tabulated by Thomas et al. (1982) and comparisons with film badge readings without accounting for the bias in badge readings are summarized as follows:[29]

- USS CABILDO at Shot DOG (April 8–13) – The reconstructed mean dose is increased to 0.14 rem. Use of a 3X upper bound factor gives an upper bound that exceeds 14 of 15 badge readings, and the highest badge reading exceeds the increased reconstructed mean dose by a factor of about 4.
- USS CURTISS at Shot EASY (April 21–26) – The reconstructed mean dose is increased to 0.040 rem. Use of a 3X upper bound factor gives an upper bound that exceeds 11 of 18 badge readings, and the highest badge reading exceeds the increased reconstructed mean dose by a factor of about 7.
- USNS SGT. CHARLES E. MOWER at Shot EASY (April 21–27) – The reconstructed mean dose is increased to 0.025 rem. Use of a 3X upper bound factor gives an upper bound that exceeds six of seven badge readings, and the highest badge reading exceeds the increased reconstructed mean dose by a factor of about 4.
- USS CABILDO at Shot ITEM (May 24–28) – The reconstructed mean dose is increased to 0.28 rem. Use of a 3X upper bound factor gives an upper bound that exceeds 12 of 16 badge readings, and the highest badge reading exceeds the increased reconstructed mean dose by a factor of about 7.
- USNS SGT. CHARLES E. MOWER at Shot ITEM (May 24–27) – The reconstructed mean dose is increased to 0.43 rem. Use of a 3X upper bound factor gives an upper bound that exceeds five of seven badge readings, and the highest badge reading exceeds the increased reconstructed mean dose by a factor of about 5.
- USS SPROSTON at Shot ITEM (May 24–25) – The reconstructed mean dose is increased to 0.003 rem. Use of a 3X upper bound factor gives an upper bound that exceeds none of the eight badge readings, and the highest badge reading exceeds the increased reconstructed mean dose by a factor of about 60.

[29] An exposure in R is multiplied by 0.7 to obtain an estimate of the film badge-equivalent dose in rem that accounts for the shielding of the film badge by the body of the wearer (Thomas et al., 1982).

Increases in reconstructed mean doses to badged participants, compared with mean doses given in the previous section, are a factor of about 1.2–3. With the possible exceptions of exposures on the USS CABILDO at Shot DOG and the USNS MOWER at Shot EASY, where only one badge reading in each case exceeds the increased reconstructed mean dose by more than a factor of three, use of a 3X upper bound factor does not give upper bounds that exceed at least 95% of all unadjusted badge readings. A tendency for the increased reconstructed doses to underestimate a substantial number of badge readings is found in cases where doses are relatively high or relatively low and in cases where exposure rates on a particular ship were measured, rather than assumed to be determined by measurements on a nearby ship or residence island.

When the bias factor of 1.4 in film badge readings at this operation is taken into account, comparisons of adjusted badge readings with the increased reconstructed mean doses that account for the greater times that badged participants presumably spent on the weather deck of ships are summarized as follows:

- USS CABILDO at Shot DOG – None of the 15 adjusted badge readings exceed the increased reconstructed mean dose by more than a factor of three.
- USS CURTISS at Shot EASY – Two of 18 adjusted badge readings (11%) exceed the increased reconstructed mean dose by more than a factor of three, and the highest adjusted badge reading exceeds the increased reconstructed mean dose by a factor of about 5.
- USNS SGT. CHARLES E. MOWER at Shot EASY – None of the seven adjusted badge readings exceed the increased reconstructed mean dose by more than a factor of three.
- USS CABILDO at Shot ITEM – Two of 16 adjusted badge readings exceed the increased reconstructed mean dose by more than a factor of three, and the highest adjusted badge reading exceeds the increased reconstructed mean dose by a factor of about 5.
- USNS SGT. CHARLES E. MOWER at Shot ITEM –Two of seven adjusted badge readings exceed the increased reconstructed mean dose by more than a factor of three, and the highest adjusted badge reading exceeds the increased reconstructed mean dose by a factor of about 4.

- USS SPROSTON at Shot ITEM – All eight adjusted badge readings exceed the increased reconstructed mean dose by more than a factor of three, and the highest adjusted badge reading exceeds the increased reconstructed mean dose by a factor of about 40.

**9.1.1.1.3** *Comparisons based on film badge readings in NuTRIS.* Comparisons of reconstructed doses with film badge readings on ships discussed previously are based on badge readings reported by Thomas et al. (1982). We also investigated whether NuTRIS gives additional badge readings for participants on ships that could be compared with reconstructed doses. In all cases listed in Section 9.1.1.1.1 except exposures on the USS CURTISS and USS SPROSTON at Shot ITEM, either the number of badge readings in NuTRIS that we assumed are relevant differs from the number of readings reported by Thomas et al. (1982) and is greater than the number of reported readings in all cases but one, or the badge readings in NuTRIS do not all agree with reported readings. In addition, in the case of exposure on the USS WALKER at Shot ITEM, where a reconstructed dose is not shown in Figure 5-4 of Thomas et al. (1982) and no film badge readings were reported, several badge readings are given in NuTRIS. Since it is not certain that badge readings in NuTRIS that were not reported by Thomas et al. (1982) apply to exposures on ships that were considered in dose reconstructions, it is questionable whether the additional badge readings in NuTRIS are relevant.

NuTRIS also gives a few film badge readings on ships that apply throughout the period from Shot DOG to the end of Operation GREENHOUSE on May 31. These badge readings are compared with total reconstructed doses given by Thomas et al. (1982) as follows:

USS CABILDO –
- Reconstructed mean dose, 0.49 rem
- Badge readings of 0.179, 0.700, and 0.807 rem

USS CURTISS –
- Reconstructed mean dose, 0.79 rem
- Badge readings of 0.373, 0.511 (three readings), and 1.043 rem

USS SPROSTON –
- Reconstructed mean dose, 0.19 rem
- Badge readings of 0.816 rem (three readings)

USS WALKER –

- Reconstructed mean dose, 0.22 (0.26) rem
- Badge reading of 0.234 rem

In each case, the highest badge reading exceeds the reconstructed mean dose by a factor of about three or less when the bias factor of 1.4 in film badge readings is taken into account. However, it is not certain that the badge readings in NuTRIS are relevant, and there are very few readings in each case. In addition, when all three badge readings on the USS SPROSTON are the same, it is questionable whether those readings apply to badges that were worn by different participants.

**9.1.1.2** *Exposures on Residence Islands*. Reconstructed mean doses on residence islands at Enewetak Atoll for the period April 8 – May 31 given by Thomas et al. (1982) are 2.93 rem on Enewetak Island, 3.10 rem on Parry Island, and 2.57 rem on Japtan Island; these doses are high compared with reconstructed mean doses to average crew members or more highly exposed badged personnel on ships. Doses on residence islands were due mainly to fallout from Shots DOG and ITEM; the estimated dose due to fallout from Shot EASY is about 0.042 rem, and there was no fallout on residence islands from Shot GEORGE. Film badge readings for participants on the residence islands were not reported by Thomas et al. (1982).

Berkhouse et al. (1983) compared readings of film badges for radiation-safety monitors in Task Unit 3.1.5 on Parry or Japtan Island that recorded exposures during the first four days after Shot DOG and were not to be worn during missions to other locations with estimates of cumulative exposure that were based on other film badge readings at fixed locations outside buildings supplemented by information from pocket dosimeters. On Parry Island, film badge readings for monitors range from 0.56 to 1.4 rem, with a mean of 0.89 rem, and the estimated dose based on other dosimeter readings is 1.19 rem; on Japtan Island, badge readings for monitors range from 0.825 to 1.6 rem, with a mean of 1.04 rem, and the dose based on other dosimeter readings is 1.3 rem.[30]

[30] NuTRIS gives one badge reading for radiation-safety monitors in Task Unit 3.1.5 of 0.23 rem on Parry Island for the period April 8–12 and badge readings of 1.225 and 1.25 rem on Japtan Island for the same period. Thus, if we assume that only those badge readings in NuTRIS that cover the entire period of interest are relevant, there appears to be little correspondence between badge readings noted by Berkhouse et al. (1983) and readings in NuTRIS.

NuTRIS gives film badge readings for many participants in units that were assigned to one of the residence islands at Enewetak Atoll. However, there are no more than four badge readings in any unit. More importantly, NuTRIS does not indicate whether recorded exposures occurred on a residence island or during a mission to another area. Therefore, comparisons of reconstructed doses with badge readings in NuTRIS probably are not meaningful.

### 9.1.2 *Exposures Following Operation*

Thomas et al. (1987) presented dose reconstructions for participants on the three residence islands at Enewetak Atoll (Enewetak, Parry, and Japtan Islands) during the period from June 1, 1951, through June 30, 1952, following completion of Operation GREENHOUSE. Monthly doses on each island during that period were calculated. Reconstructed mean doses for the entire period are 2.03 rem on Enewetak Island, 1.76 rem on Parry Island, and 1.45 rem on Japtan Island. Mean doses are about 55–70% of the reconstructed mean doses during the entire period of the operation from April 8 to May 31, 1951. Film badge readings for participants on residence islands during the post-operation period were not reported by Thomas et al. (1987), and NuTRIS does not give any badge readings during this period.

## 9.2 SAIC Memoranda

Many memoranda that addressed exposures of particular units during Operation GREENHOUSE that were not considered in the unit dose reconstructions discussed in Section 9.1.1 were prepared by SAIC (Gminder, 1981; Thomas, 1988; Martinez, 1995a–i, 1996, 1997; Cockayne, 1995a,b). Only one of those memoranda gives additional information on comparisons of reconstructed external gamma doses with film badge readings.

Thomas (1988) addressed exposure of participants in a military police company on Enewetak Island and on two non-residence islands (Aomon and Engebi) at or closer to locations of detonations. Comparisons of reconstructed mean doses with average film badge readings given by Thomas (1988) are summarized as follows:

Enewetak Island –

April 8–19 –

– Reconstructed mean dose, 0.45 rem

– Average film badge reading, 0.51 rem (5 total badges)

April 20 – May 3 –

– Reconstructed mean dose, 0.08 rem

– Average film badge reading, 0.09 rem (6 total badges)

Aomon Island –

April 22 – May 1 –

– Reconstructed mean dose, 0.66 rem

– Average film badge reading, 0.71 rem (28 total badges)

Engebi Island –

April 27 – May 3 –

– Reconstructed mean dose, 0.125 rem

– Average film badge reading, 0.17 rem (10 total badges)

April 27 – May 17 –

– Reconstructed mean dose, 0.205 rem

– Film badge reading, 0.33 rem

April 28 – May 3 –

– Reconstructed mean dose, 0.09 rem

– Average film badge reading, 0.09 rem (5 total badges)

May 3–17 –

– Reconstructed mean dose, 0.08 rem

– Average film badge reading, 0.12 rem (12 total badges)

In all cases, the average film badge reading does not exceed the reconstructed mean dose by more than a factor of about 1.5 without accounting for the bias factor of 1.4 in badge readings.

We also investigated whether NuTRIS gives film badge readings for the cases summarized above. Ranges of badge readings in NuTRIS are as follows:

Enewetak Island –

April 8–19, 0.41–0.55 rem (5 total badges)

April 20 – May 3, 0.08–0.13 rem (6 total badges)

Aomon Island –

April 22 – May 1, 0.44–1.05 rem (28 total badges)

Engebi Island –

April 27 – May 3, 0.13–0.31 rem (8 total badges)

April 27 – May 17, no badge readings

April 28 – May 3, 0.07–0.165 rem (3 total badges)

May 3–17, no badge readings

In the cases where badge readings are given in NuTRIS, they are consistent with average badge readings reported by Thomas (1988),[31] and they indicate that the highest badge reading exceeds the reconstructed mean dose by less than a factor of three in all cases without accounting for the bias in badge readings.

### 9.3 Summary of Analysis

Comparisons of reconstructed doses from external exposure to residual gamma radiation with relevant film badge readings can be made only for exposures during Operation GREENHOUSE (i.e., during the period April 8 – May 31, 1951). Comparisons cannot be made during the post-operation period, when substantial doses continued to be received by personnel stationed on residence islands (Enewetak, Parry, and Japtan).

Comparisons of reconstructed mean doses on ships with film badge readings given in published reports or SAIC memoranda and more limited comparisons on residence islands and other non-residence islands are summarized as follows:

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[31] There is no apparent explanation for the absence in NuTRIS of badge readings on Engebi Island during the periods April 27 – May 17 and May 3–17, when badge readings were reported by Thomas (1988).

- In 11 of 15 cases of exposure on ships at Shots DOG, EASY, and ITEM, use of a 3X upper bound factor gives upper bounds of reconstructed external gamma doses that are at least upper 95% confidence limits when compared with film badge readings reported by Thomas et al. (1982) that are adjusted to account for the bias factor of 1.4 in badge readings at this operation, provided that reconstructed mean doses for average crew members are increased to better represent the presumed higher exposures of badged participants. The higher exposures were assumed to result from longer exposure times for badged participants on the weather deck compared with exposure times for average crew members (Thomas et al., 1982).
- The four cases of exposure on ships at Shots DOG, EASY, and ITEM where use of a 3X upper bound factor gives upper bounds of reconstructed doses that are not at least upper 95% confidence limits when reconstructed mean doses given by Thomas et al. (1982) are increased to better represent the presumed higher exposures of badged participants compared with average crew members include the USS CURTISS at Shot EASY and the USS CABILDO, USNS SGT. CHARLES E. MOWER, and USS SPROSTON at Shot ITEM. When the bias factor of 1.4 in film badge readings is taken into account, an upper bound factor of about 4–5 is required in the first three cases, and an upper bound factor of about 40 is required in the fourth case. In two of these cases, reconstructed doses were based on measured exposure rates on the ship.
- Limited comparisons of reconstructed doses on residence or non-residence islands with film badge readings for participants (Berkhouse et al., 1983; Thomas, 1988) indicate that use of a 3X upper bound factor gives upper bounds of reconstructed doses that are at least upper 95% confidence limits.

Discrepancies in the four cases on ships where some adjusted film badge readings exceed an increased reconstructed mean dose by more than a factor of three do not have an apparent explanation. Higher badge readings on the USS CURTISS at Shot EASY, where the reconstructed dose is relatively low, may have been due to exposure to radioactive sources that were used to calibrate survey instruments, since repair facilities for those instruments were located on that ship (Berkhouse et al., 1983); this also is a case where exposure rates on the ship were not measured but were assumed to be the same as on a nearby ship, and estimated exposure

rates could be less reliable in such cases. A lack of measured exposure rates on a ship also is a concern in reconstructing doses on the USNS MOWER at Shot ITEM, but not on the USS CABILDO and SPROSTON at that shot.

In regard to exposure on the USS SPROSTON at Shot ITEM, where all film badge readings are much higher than the reconstructed mean dose, Cockayne (1998) considered the available dosimetry information and concluded that a total exposure of 1 R that was reported in medical records on the basis of a May 23, 1951, memorandum does not reflect the best available data and should be superseded for generic, unbadged crew members by reconstructed daily doses given by Thomas et al. (1982) and discussed in Section 9.1.1.1.1. However, the assessment by Cockayne (1998) did not address the eight badge readings of 0.08–0.18 rem on the USS SPROSTON during the period May 24–25 that were reported by Thomas et al. Furthermore, the large discrepancies between the badge readings and reconstructed mean dose cannot be explained by assuming that badged participants were exposed on the weather deck for a majority of the time. In the other cases where an assumption of higher exposure times on deck was used in reconstructing doses, the increase in mean dose is less than a factor of three. If a similar increase applies to badged participants on the USS SPROSTON at Shot ITEM, as assumed in this analysis, all badge readings are still more than an order of magnitude higher than the reconstructed mean dose. There is no apparent explanation for the large discrepancy in this case.

At Shot GEORGE, one of seven film badge readings on the USNS MOWER and one of 17 badge readings on the USS WALKER are above a nominal minimum detectable dose of 50 mrem and exceed the reconstructed mean dose of 10 mrem or less by large factors. However, given the absence of fallout on ships at that shot (Thomas et al., 1982), the high badge readings probably are anomalous and not indicative of exposures of average crew members.

## References

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# 10. OPERATIONS AT PPG – IV.
# OPERATION IVY (1952)

## 10.1 Published Unit Dose Reconstructions

Dose reconstructions for military units at Operation IVY, which was conducted at Enewetak Atoll, are given in a published report by Thomas et al. (1983). Those dose reconstructions are concerned with exposure of naval units on ships and personnel based on Enewetak Atoll (Enewetak Island and Parry Island), Kwajalein Atoll, or Bikini Atoll to residual gamma radiation due mainly to secondary (late-time) fallout from Shot MIKE on November 1. Exposures to fallout from Shot KING on November 16 also were included in dose reconstructions but were much less important.

### **10.1.1** *Exposures on Ships*

Thomas et al. (1983) presented reconstructed cumulative doses for naval personnel on 18 ships during the period October 31 – November 17 or 18, when Operation IVY essentially ended. Doses were estimated by integrating measured or assumed exposure rates over time and taking into account the shielding provided by a ship's structure when participants were below the weather deck. Reconstructed mean doses during the entire period of the operation are low, ranging from 1 to 62 mrem, and are below a nominal minimum detectable dose of 50 mrem (see Section 1.4) on 17 of the 18 ships.

On 14 of the 18 ships, Thomas et al. (1983) compared reconstructed doses with film badge readings for personnel on those ships; there were no badge readings on the other four ships. These comparisons are summarized as follows:[32]

[32] Film badge readings are estimated from Figure 5-1 of Thomas et al. (1983). Reconstructed mean doses are obtained from Table 6-1 of that report when the period during which comparisons are made in Figure 5-1 extends to November 17 or 18; when the comparison period is shorter, which occurred on six ships, reconstructed mean doses are estimated from Figure 5-1.

USS RENDOVA (October 31–November 5) –

- Reconstructed mean dose, 6 mrem
- Range of badge readings, 0–2,280 mrem (208 total badges)
- Badge readings above nominal detectable dose of 50 mrem, 18
- Badge readings of zero, 142

USS OAK HILL (October 31–November 18) –

- Reconstructed mean dose, 34 mrem
- Range of badge readings, 0–460 mrem (67 total badges)
- Badge readings above nominal detectable dose of 50 mrem, 26
- Badge readings of zero, 14

USS ARIKARA (October 31–November 7) –

- Reconstructed mean dose, 15 mrem
- All badge readings, 0 (14 total badges)

USS LIPAN (October 31–November 17) –

- Reconstructed mean dose, 36 mrem
- Range of badge readings, 40–70 mrem (12 total badges)
- Badge readings above nominal detectable dose of 50 mrem, 6

USS DAVID C. SHANKS (October 31–November 10) –

- Reconstructed mean dose, 23 mrem
- Range of badge readings, 26–50 mrem (8 total badges)

USS AGAWAM (October 31–November 17) –

- Reconstructed mean dose, 23 mrem
- Range of badge readings, 0–115 mrem (22 total badges)
- Badge readings above nominal detectable dose of 50 mrem, 13
- Badge readings of zero, 3

USS ESTES (October 31–November 18) –

- Reconstructed mean dose, 24 mrem
- Range of badge readings, 0–1,630 mrem (98 total badges)
- Badge readings above nominal detectable dose of 50 mrem, 63
- Badge readings of zero, 4

USS ELDER (October 31–November 6) –

- Reconstructed mean dose, 9 mrem
- Range of badge readings, 0–36 mrem (14 total badges)
- Badge readings of zero, 5

USS CARPENTER (October 31–November 17) –

- Reconstructed mean dose, 11 mrem
- Range of badge readings, 30–130 mrem (21 total badges)
- Badge readings above nominal detectable dose of 50 mrem, 17

USS O'BANNON (October 31–November 17) –

- Reconstructed mean dose, 5 mrem
- Range of badge readings, 0–220 mrem (22 total badges)
- Badge readings above nominal detectable dose of 50 mrem, 12
- Badge readings of zero, 3

USS FLETCHER (October 31–November 17) –

- Reconstructed mean dose, 13 mrem
- Range of badge readings, 40–115 mrem (20 total badges)
- Badge readings above nominal detectable dose of 50 mrem, 15

USS YUMA (October 31–November 17) –

- Reconstructed mean dose, 9 mrem
- Range of badge readings, 0–130 mrem (12 total badges)
- Badge readings above nominal detectable dose of 50 mrem, 10
- Badge readings of zero, 1

USS CURTISS (October 31–November 6) –

- Reconstructed mean dose, 3 mrem
- All badge readings, 0 (17 total badges)

M/V HORIZON (October 31–November 6) –

- Reconstructed mean dose, 35 mrem
- Range of badge readings, 0–86 mrem (28 total badges)
- Badge readings above nominal detectable dose of 50 mrem, 9
- Badge readings of zero, 3

Reconstructed doses on the USS LIPAN, ARIKARA, DAVID C. SHANKS, ELDER, and YUMA were based on measured exposure rates on nearby ships or islands. On the other nine ships, reconstructed doses were based on measured exposure rates on those ships.

On six ships—the USS ARIKARA, LIPAN, DAVID C. SHANKS, ELDER, and CURTISS and the M/V HORIZON—film badge readings do not differ greatly from the reconstructed mean dose. Except on the USS ELDER, the highest badge reading on each of these ships is within a factor of three of the reconstructed mean dose without accounting for the bias of a factor of 1.5 in film badge readings at this operation (see Table 1.1). On the USS ELDER, the highest badge reading also is within a factor of three of the reconstructed mean dose when the bias in badge readings is taken into account. Since all badge readings on the USS ELDER are less than a nominal minimum detectable dose of 50 mrem, a comparison of the reconstructed dose with badge readings is not meaningful.

On the other eight ships listed above, a substantial fraction of film badge readings that exceed a nominal minimum detectable dose of 50 mrem are well above the reconstructed mean dose. Thomas et al. (1983) offered explanations of the higher film badge readings compared with reconstructed doses on all these ships except the USS AGAWAM. Those explanations are discussed below. Additional information obtained from NuTRIS also is discussed.

Thomas et al. (1983) attributed the relatively few high film badge readings on the USS RENDOVA to exposure of participants who were issued badges when they were expected to enter contaminated areas other than those routinely encountered on that ship. Thomas et al. also noted that the large number of zero badge readings (68%) is indicative of low exposures of crew members. This explanation is consistent with information in NuTRIS, which indicates that nearly 90% of all badges with readings above a nominal minimum detectable dose of 50 mrem were issued to members of air units or Task Group 132.3, which carried out the radiation safety program during Operation IVY (Gladeck et al., 1982); only nine badge readings above 50 mrem in NuTRIS do not apply to identified members of those units. A more detailed comparison of film badge readings in NuTRIS with badge readings shown in Figure 5-1 of Thomas et al. (1983) may not be meaningful when the end date of readings reported by Thomas et al. is November 5 but the end date of all readings in NuTRIS is November 17 or later. The end dates in NuTRIS may be defaults that essentially correspond to the end of Operation IVY, rather than the end of periods of exposure. Nonetheless, if data in NuTRIS are indicative of the number of crew

members on the USS RENDOVA who received unusually high doses, it appears that fewer than 5% of all badge readings (about nine of 208 readings) for crew members exceed the reconstructed mean dose by more than a factor of three and are above 50 mrem. Given the very low reconstructed mean dose of 6 mrem, the number of such readings does not depend on whether the bias factor of 1.5 in badge readings is taken into account.

Thomas et al. (1983) attributed the higher film badge readings on the USS OAK HILL to exposure of members of a boat pool who were issued badges when they were expected to enter contaminated areas other than those routinely encountered on that ship. Information in NuTRIS does not allow a distinction between badge readings for members of a boat pool and readings for other personnel on the USS OAK HILL; although a boat group is identified as a separate unit, NuTRIS does not give any badge readings for members of that group. Eight badge readings (12%) reported by Thomas et al. (1983) exceed the reconstructed mean dose by more than a factor of three when the bias factor of 1.5 in badge readings is taken into account.

Thomas et al. (1983) attributed the higher film badge readings on the USS ESTES to exposure of members of helicopter units who were issued badges when they were expected to enter contaminated areas other than those routinely encountered on that ship. Higher exposures were assumed to occur while members of those units were located near a contaminated helicopter pad on the ship's weather deck, as well as during missions away from the ship. Exposures near the helicopter pad were not taken into account in reconstructing doses to an average crew member. The reconstructed mean dose to participants who spent time near the helicopter pad is 72 mrem. However, Thomas et al. (1983) did not distinguish between badge readings for members of helicopter units who were exposed away from the ship and members of those units who were exposed at the helicopter pad, and information in NuTRIS does not allow a distinction between badge readings for members of helicopter units and readings for other personnel on the USS ESTES. About 20 of the 98 badge readings (about 20%) reported by Thomas et al. (1983) exceed the reconstructed mean dose by more than a factor of three when the bias factor of 1.5 in badge readings is taken into account.

Thomas et al. (1983) speculated that nearly all of the higher film badge readings on the USS CARPENTER, O'BANNON, and FLETCHER may have been due to contamination of those ships' hulls that occurred as they patrolled in areas where much of the fallout from Shot MIKE was deposited. However, the presence of contamination on the ships' hulls was not

verified, and there were no data that could be used to estimate the extent of contamination and associated doses. All but four badge readings on the USS CARPENTER, all but seven readings on the USS O'BANNON, and all but five readings on the USS FLETCHER reported by Thomas et al. (1983) are above a nominal minimum detectable dose of 50 mrem and exceed the reconstructed mean dose by more than a factor of three when the bias factor of 1.5 in badge readings is taken into account.

Finally, Thomas et al. (1983) concluded that a comparison between the reconstructed dose to a crew member on the USS YUMA and film badge readings cannot be made. Records indicate that badges were turned in and processed on November 17. However, Thomas et al. (1983) argued that this turn-in date is unlikely to be correct, because the USS YUMA left Enewetak Atoll on November 8 and film badges probably were turned in prior to departure. If badges were not processed until November 17, recorded exposures would have included contributions from fallout at the atoll that were not received by crew members, who departed with the ship. All but two badge readings are above a nominal minimum detectable dose of 50 mrem and exceed the reconstructed mean dose by more than a factor of three when the bias factor of 1.5 in badge readings is taken into account.

Thomas et al. (1983) did not offer an explanation for the higher film badge readings on the USS AGAWAM compared with the reconstructed mean dose but noted that badge readings are similar to reconstructed doses on the USS OAK HILL and LIPAN, which were anchored several miles southwest of the USS AGAWAM during the same period. In this case, however, only one of 22 badge readings exceeds the reconstructed mean dose by more than a factor of three when the bias factor of 1.5 in badge readings is taken into account.

On the basis of information discussed above, we offer the following opinions about the eight cases on ships where reconstructed mean doses generally are well below a substantial fraction of film badge readings.

On the USS RENDOVA, it appears likely that fewer than 5% of all film badge readings for crew members (i.e., participants who were not members of air units or Task Group 132.3) exceed the reconstructed mean dose by more than a factor of three. It also appears that members of units that received doses higher than many crew members can be identified.

On the USS OAK HILL, the reconstructed mean dose may not differ greatly from film badge readings for crew members who were not members of a boat pool. However, members of

the boat pool are not identified in NuTRIS. Therefore, given that a reconstructed mean dose of 34 mrem or less is assigned in NuTRIS to nearly all unbadged participants on this ship, the dose to a member of the boat pool could be underestimated by more than a factor of three if a badge reading is not available.

On the USS ESTES, film badge readings for most crew members who were not members of helicopter units may not exceed the reconstructed mean dose by more than a factor of three. However, a reconstructed dose of 22 mrem, which is consistent with the mean dose of 24 mrem given by Thomas et al. (1983), is assigned in NuTRIS to all unbadged participants on this ship. Thus, it appears that the higher reconstructed mean dose of 72 mrem for participants who were exposed near the contaminated helicopter pad on the ship's weather deck has not been assigned to any unbadged participant. Unless all members of helicopter units who were exposed near the contaminated pad have badge readings, the dose to unbadged members of those units could exceed the reconstructed mean dose by more than a factor of three.

The unsubstantiated assumption that higher film badge readings on the USS CARPENTER, O'BANNON, and FLETCHER could have been due to the presence of contamination on those ships' hulls that was not considered in the dose reconstruction may be plausible. However, this explanation raises a concern about doses that would be assigned to unbadged participants. Reconstructed doses that are assigned to unbadged participants in NuTRIS are similar to the low reconstructed mean doses on those ships given by Thomas et al. (1983). However, all personnel on the USS CARPENTER, O'BANNON, and FLETCHER presumably were exposed during normal activities on those ships when Thomas et al. (1983) gives no indication to the contrary. If this were the case, use of a 3X upper bound factor on the reconstructed mean doses would not give an upper bound that exceeds the dose to at least 95% of all participants. The extent of this discrepancy, as indicated by comparisons of reconstructed mean doses with film badge readings above a nominal minimum detectable dose of 50 mrem that are adjusted to account for the bias factor of 1.5 in badge readings, is summarized as follows:

- On the USS CARPENTER, 17 of 21 adjusted badge readings above 50 mrem exceed three times the reconstructed mean dose. To obtain an upper bound that exceeds at least 95% of all adjusted badge readings, an upper bound factor of about 8 is required.

- On the USS O'BANNON, 15 of 22 adjusted badge readings above 50 mrem exceed three times the reconstructed mean dose. To obtain an upper bound that exceeds at least 95% of all adjusted badge readings, an upper bound factor of about 25 is required.
- On the USS FLETCHER, 15 of 20 adjusted badge readings above 50 mrem exceed three times the reconstructed mean dose. To obtain an upper bound that exceeds at least 95% of all adjusted badge readings, an upper bound factor of about 6 is required.

An alternative approach to ensure that doses to at least 95% of unbadged participants on those three ships are not underestimated would be to assign mean doses on the basis of distributions of film badge readings on each ship, rather than reconstructed mean doses given by Thomas et al. (1983). This approach may be preferable when the dose reconstruction did not consider the potentially most important source of exposure (contamination on the ships' hulls).

We believe it is questionable that film badge readings for participants on the USS YUMA are much higher than actual exposures of crew members during the period up to the time of departure from Enewetak Atoll on November 8. The USS YUMA was located near Kwajalein Atoll on November 2–4 when the heaviest fallout from Shot MIKE occurred and was stationed at Enewetak Atoll when lower levels of fallout from that shot occurred on November 7–8 (Thomas et al., 1983). Since there was no record of measurements of exposure rates on the USS YUMA, exposures during the period November 2–4 were estimated on the basis of average exposure rates on Kwajalein Atoll. Given that the maximum exposure rate on the atoll was about three times higher than the average exposure rate (Thomas et al., 1983), the average exposure rate on the atoll could have been substantially lower than the average exposure rate on the ship. Furthermore, reconstructed cumulative exposures on ships at Enewetak Atoll due to fallout that occurred on November 7–8 and November 16–17 (Thomas et al., 1983; Table 2-1) indicate that cumulative doses at that location during the period November 7–18 due only to fallout after the USS YUMA arrived at Enewetak Atoll were less than 10 mrem. If the reconstructed dose while the ship was located near Kwajalein Atoll is a reasonable estimate, doses due to fallout that occurred after the ship's arrival at Enewetak Atoll on November 7 would need to be substantially higher than 10 mrem to explain readings of ten of the total of 12 film badges that exceed a nominal minimum detectable dose of 50 mrem. On the basis of these considerations, it may not be reasonable to conclude that the reconstructed dose did not substantially underestimate doses

to crew members. An upper bound factor of about 7 is required to obtain an upper bound that exceeds at least 95% of the film badge readings.

On the USS AGAWAM, where Thomas et al. (1983) did not offer an explanation of the higher film badge readings compared with the reconstructed dose, a discussion in Section 2.2.5 of that report suggests that measurements of exposure rates that were used to reconstruct doses on that ship were sparse. As noted previously, however, only one of 22 badge readings exceeds the reconstructed mean dose by more than a factor of three when the bias factor of 1.5 in badge readings is taken into account. Thus, use of a 3X upper bound factor is adequate in this case.

### **10.1.2** *Exposures on Residence Islands*

Thomas et al. (1983) estimated doses to participants on residence islands at Enewetak, Kwajalein, and Bikini Atolls by integrating measured exposure rates over time and taking into account the shielding provided by buildings when participants were indoors. Reconstructed mean doses during the period October 31 – November 17 or 18 are low, ranging from 2 to 59 mrem, and are below a nominal minimum detectable dose of 50 mrem on three of the four residence islands.

Thomas et al. (1983) did not report any film badge readings for participants on residence islands. Although NuTRIS gives badge readings for participants on those islands, many badge readings apply to time periods sufficiently short that they probably were mission badges, and it is not possible to determine on the basis of information in NuTRIS whether badge readings during longer time periods apply to exposures on residence islands only. Therefore, comparisons of reconstructed mean doses with badge readings in NuTRIS probably are not meaningful.

## 10.2 SAIC Memoranda

Several memoranda that addressed exposures of particular units during Operation IVY that were not considered in the unit dose reconstructions discussed in Section 10.1 were prepared by SAIC (Gminder, 1981; Thomas, 1989a,b; Martinez, 1995a,b; Weitz, 2000). Only one of those memoranda gives additional information on comparisons of reconstructed external gamma doses with film badge readings.

Thomas (1989b) addressed exposures of participants in a military police company on Enewetak or Parry Island and on two non-residence islands (Runit and Dridrilbwij) at or closer to locations of detonations. However, reconstructed doses for specific individuals apply to the entire time this company was stationed at Enewetak Atoll, whereas film badge readings for some of those participants reported by Thomas (1989b) apply only to periods of about 10 days or less and many readings apply to a single day. Thus, reconstructed doses for individual members of this company cannot be compared with badge readings.

Reconstructed cumulative doses to participants in another unit that was stationed on Enewetak and Parry Island were given by Gminder (1981). However, reconstructed doses are much higher than later estimates by Thomas et al. (1983) and Thomas (1989a). Therefore, we presume that the dose reconstruction by Gminder (1981) has been superseded.

### 10.3 Summary of Analysis

Published unit dose reconstructions provide comparisons of reconstructed doses from external exposure to residual gamma radiation at Operation IVY with relevant film badge readings only in cases of exposure to fallout on ships. An SAIC memorandum provides additional information about exposures on Enewetak or Parry Island, but a meaningful comparison of reconstructed doses with film badge readings cannot be made when reconstructed doses apply to longer time periods than the badge readings and some badge readings include exposures at other locations.

On 14 ships, reconstructed mean doses that were intended to apply to average crew members can be compared with film badge readings. On seven ships, there is good agreement between reconstructed mean doses and film badge readings when the preponderance of badge readings below a nominal minimum detectable dose of 50 mrem on six of those ships and the bias factor of 1.5 in film badge readings at this operation are taken into account, and use of a 3X upper bound factor is adequate. Furthermore, on three of the seven ships where reconstructed mean doses generally are substantially lower than film badge readings (the USS RENDOVA, OAK HILL, and ESTES), most of the higher badge readings probably apply to personnel in units that received higher exposures than typical crew members during special activities that were not taken into account in dose reconstructions (Thomas et al., 1983). We believe that use of a 3X

upper bound factor gives upper bounds that are at least 95% confidence limits of doses to average crew members on those three ships.

On four ships, however, reconstructed mean doses consistently underestimate film badge readings that presumably apply to crew members. On three ships—the USS CARPENTER, O'BANNON, and FLETCHER—most badge readings exceed the reconstructed mean dose by more than a factor of three when the bias factor of 1.5 in film badge readings is taken into account. An upper bound factor of about 8 on the USS CARPENTER, 25 on the USS O'BANNON, and 6 on the USS FLETCHER is required to give upper bounds that are at least 95% confidence limits. These large discrepancies could be due to unsubstantiated contamination on those ships' hulls that could not be considered in dose reconstructions (Thomas et al., 1983). An assumption of an inadequate exposure scenario would not be an important concern if distributions of film badge readings were used to estimate doses to unbadged participants on those ships. However, information in NuTRIS and the *Standard Operating Procedures Manual* (DTRA, 2008; Appendix B-4) indicates that reconstructed mean doses reported by Thomas et al. (1983) are assigned to all unbadged participants on those ships. This procedure probably results in substantial underestimates of mean doses and upper bounds to those participants.

On the fourth ship—the USS YUMA—where exposure rates were assumed to be determined by measurements on Kwajalein Atoll and on other ships at Enewetak Atoll, the high film badge readings compared with the reconstructed mean dose were attributed to exposures between the time this ship left Enewetak Atoll, when badges presumably were turned in, and the time more than a week later when badges presumably were processed (Thomas et al., 1983). However, estimates of exposures on other ships during that period may not be sufficient to explain the high badge readings, and it may not be reasonable to conclude that the reconstructed mean dose does not substantially underestimate doses to crew members. An upper bound factor of about 7 is required to give an upper bound that is at least a 95% confidence limit.

It also is important to emphasize that doses to crew members on ships at Operation IVY were low. On the USS CARPENTER, O'BANNON, FLETCHER, and YUMA, where reconstructed mean doses generally are substantially less than film badge readings (i.e., use of a 3X upper bound factor gives upper bounds that do not exceed at least 95% of all badge readings) and there is no evident explanation of the discrepancies, the highest badge reading reported by Thomas et al. (1983) is 220 mrem on the USS O'BANNON, and all reported badge readings on

the other three ships are 130 mrem or less. Exposures on ships at this operation do not provide an opportunity to evaluate the adequacy of a 3X upper bound factor at higher residual gamma doses. We also note that some discrepancies between reconstructed doses and film badge readings on ships may reflect difficulties in measuring low exposure rates and the need to estimate exposures on the USS YUMA, where measurements were lacking, on the basis of measurements on nearby ships or islands (Thomas et al., 1983; DTRA, 2008; Appendix B-4). Overall, however, discrepancies do not tend to occur more frequently on ships where exposure rates were not measured.

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# 11. OPERATIONS AT PPG – V.
# OPERATION CASTLE (1954)

## 11.1 Published Unit Dose Reconstructions

Dose reconstructions for military units at Operation CASTLE, which was conducted at Bikini and Enewetak Atolls, are given in published reports by Thomas et al. (1984), Goetz et al. (1987), and Thomas et al. (1991). All dose reconstructions are concerned with exposure to residual gamma radiation due to fallout from the six shots at this operation (Shot BRAVO on March 1, Shot ROMEO on March 27, Shot KOON on April 7, Shot UNION on April 26, Shot YANKEE on May 5, and Shot NECTAR on May 14). The initial dose reconstructions by Thomas et al. (1984) considered exposures on 16 ships where available film badge readings were insufficient to assess doses to all crew members and exposures on residence islands at Enewetak and Kwajalein Atolls where badge readings were lacking. Dose reconstructions by Thomas et al. (1991) extended the analyses by Thomas et al. (1984) to include eight additional ships where available film badge readings were insufficient to assess doses to all crew members. The dose reconstruction by Goetz et al. (1987) considered a special case of service personnel stationed on Rongerik Atoll who received unusually high doses due to fallout from Shot BRAVO.

### 11.1.1 *Exposures on Ships*

**11.1.1.1** *Comparisons Based on Film Badge Readings in Unit Dose Reconstructions*. Of the 16 ships that were considered in dose reconstructions performed by Thomas et al. (1984), reconstructed doses to an average crew member were compared with film badge readings on only three ships (the USS ESTES, PHILIP, and SIOUX), whereas comparisons were provided on all eight ships that were considered in dose reconstructions performed by Thomas et al. (1991). The relevant film badge readings are readings of cohort badges that were issued to selected individuals and were assumed to represent doses to other crew members who performed similar duties in the same area on a ship. Mission badges that were issued to participants when they were expected to enter contaminated areas other than those encountered on ships were not included in comparisons with reconstructed doses.

Reconstructed mean doses to average crew members on 11 ships during defined time periods are compared with film badge readings on the basis of information given in Thomas et al. (1984; 1991) as follows:[33]

USS ESTES –

February 28 – March 9 –

– Reconstructed mean dose, 1.32 rem[34]

– Range of film badge readings, 0–6.0 rem (49 total badges)

March 10 – May 3 –

– Reconstructed mean dose, 0.56 rem

– Range of film badge readings, 0.1–2.0 rem (48 total badges)

May 4 – May 14 –

– Reconstructed mean dose, 0.027 rem

– Range of film badge readings, 0–0.54 rem (52 total badges)

February 28 – May 14 –

– Reconstructed mean dose, 1.93 rem

– Range of film badge readings, 0.5–8.0 rem (39 individuals)

USS PHILIP –

February 25 – March 5 –

– Reconstructed mean dose, 2.00 rem[35]

– Range of film badge readings, 0.5–6.5 rem (35 total badges)

March 6 – May 2 –

– Reconstructed mean dose, 1.04 rem

– Range of film badge readings, 0–1.1 rem (34 total badges)

[33]Reconstructed mean doses are tabulated values and exclude doses to participants who were involved in decontamination activities on the USS ESTES or USS PHILIP after Shot BRAVO on March 1. Ranges of film badge readings, which were not tabulated, are estimated from histograms given in figures (Thomas et al., 1984; 1991); these ranges may overestimate actual ranges of badge readings. On the USS ESTES, PHILIP, and SIOUX, entries for the period from February 24, 25, or 28 through May 14 or 16 are reconstructed mean doses for the entire period of the operation and sums of film badge readings for the relatively few participants with badge readings for all three shorter periods.

[34] Reconstructed mean dose during decontamination activities on March 1 is 0.28 rem.

[35] Reconstructed mean dose during decontamination activities on March 1 is 0.43 rem.

May 3 – May 14 –

- Reconstructed mean dose, 0.42 rem
- Range of film badge readings, 0.05–0.25 rem (25 total badges)

February 25 – May 14 –

- Reconstructed mean dose, 3.6 rem
- Range of film badge readings, 1.4–4.2 rem (16 individuals)

USS SIOUX –

February 24 – March 7 –

- Reconstructed mean dose, 0.31 rem
- Range of film badge readings, 0.15–0.75 rem (15 total badges)

March 8 – April 11 –

- Reconstructed mean dose, 0.80 rem
- Range of film badge readings, 0.1–0.95 rem (10 total badges)

April 12 – May 16 –

- Reconstructed mean dose, 0.64 rem
- Range of film badge readings, 0.3–0.9 rem (14 total badges)

February 24 – May 16 –

- Reconstructed mean dose, 1.8 rem
- Range of film badge readings, 0.8–2.3 rem (9 individuals)

USS RECLAIMER –

April 13 – April 19 –

- Reconstructed mean dose, 0.026 rem
- Range of film badge readings, 0–0.2 rem (13 total badges)

April 20 – April 27 –

- Reconstructed mean dose, 0.033 rem
- Range of film badge readings, 0–0.4 rem (42 total badges)

April 28 – May 3 –

- Reconstructed mean dose, 0.13 rem
- Range of film badge readings, 0–0.5 rem (82 total badges)

USS SHEA –

March 30 – May 2 –

- Reconstructed mean dose, 0.32 rem
- Range of film badge readings, 0–0.4 rem (21 total badges)

USS COCOPA –

February 23 – March 6 –

- Reconstructed mean dose, 0.80 rem
- Range of film badge readings, 0.4–1.1 rem (7 total badges)

March 10 – April 29 –

- Reconstructed mean dose, 0.87 rem
- Range of film badge readings, 0–1.2 rem (12 total badges)

May 1 – May 7 –

- Reconstructed mean dose, 0.22 rem
- Range of film badge readings, 0.1–1.0 rem (11 total badges)

May 8 – May 18 –

- Reconstructed mean dose, 0.07 rem
- Range of film badge readings, 0.1–1.0 rem (12 total badges)

USS MENDER –

March 27 – April 27 –

- Reconstructed mean dose, 0.59 rem
- Range of film badge readings, 0.1–0.6 rem (3 total badges)

April 30 –

- Reconstructed mean dose, 0.25 rem
- Range of film badge readings, 0.1–0.4 rem (5 total badges)

May 1 – May 10 –

- Reconstructed mean dose, 0.35 rem
- Range of film badge readings, 0.1–0.6 rem (10 total badges)

USS MOLALA –

February 28 – March 5 –

- Reconstructed mean dose, 0.069 rem
- Range of film badge readings, 0–0.25 rem (81 total badges)

March 13 – March 30 –

- Reconstructed mean dose, 0.35 rem
- Range of film badge readings, 0.1–0.45 rem (12 total badges)

March 31 – April 11 –

- Reconstructed mean dose, 0.58 rem
- Range of film badge readings, 0–1.19 rem (81 total badges)

April 12 – May 2 –

- Reconstructed mean dose, 0.14 rem
- Range of film badge readings, 0.1–1.3 rem (57 total badges)

May 4 – May 7 –

- Reconstructed mean dose, 0.17 rem
- Range of film badge readings, 0–0.80 rem (82 total badges)

May 8 – May 16 –

- Reconstructed mean dose, 0.43 rem
- Range of film badge readings, 0–0.9 rem (78 total badges)

USS TAWAKONI –

February 28 – March 7 –

- Reconstructed mean dose, 0.24 rem
- Range of film badge readings, 0–0.5 rem (10 total badges)

March 12 – May 3,4 –

- Reconstructed mean dose, 0.45 rem
- Range of film badge readings, 0–0.5 rem (9 total badges)

May 3,4 – May 8 –

- Reconstructed mean dose, 0.18 rem
- Range of film badge readings, 0–0.8 rem (7 total badges)

USS PC-1546 –

February 24 – March 6 –

- Reconstructed mean dose, 0.74 rem
- Range of film badge readings, 0.5–0.8 rem (4 total badges)

March 7 – April 30 –

- Reconstructed mean dose, 0.69 rem
- Range of film badge readings, 0–0.4 rem (4 total badges)

USS LST-1146 –

March 19 – April 3 –

- Reconstructed mean dose, 0.19 rem
- Range of film badge readings, 0–0.3 rem (12 total badges)

In several cases, exposure rates were not measured on a ship, and reconstructed doses were based in part on measurements on nearby ships or islands. These cases include exposures on the USS RECLAIMER and TAWAKONI during all periods, the USS MOLALA during the first and last period, and the USS PC-1546 during the second period (Thomas et al., 1991).

In several comparisons summarized above, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that does not exceed at least 95% of the film badge readings without accounting for the bias of a factor of 1.3 in badge readings at this operation (see Table 1.1). Unadjusted badge readings that exceed the reconstructed mean dose by more than a factor of three, as estimated from information given in histograms (Thomas et al., 1984; 1991), are summarized as follows:

- USS ESTES (February 28 – March 9) – four of 49 badge readings exceed the upper bound for an average crew member, with the highest badge reading exceeding the reconstructed mean dose of 1.32 rem by a factor of about 4.5, but only two badge readings (< 5%) exceed the upper bound for members of a decontamination crew;
- USS ESTES (May 4–14) – about 48 of 52 badge readings, with the highest badge reading exceeding the reconstructed mean dose of 0.027 rem by a factor of about 20;
- USS ESTES (February 28 – May 14) – four of 39 badge readings exceed the upper bound for an average crew member, with the highest badge reading exceeding the reconstructed

mean dose of 1.93 rem by a factor of about 4, but no more than two badge readings (5%) exceed the upper bound for members of a decontamination crew;[36]

- USS RECLAIMER (April 20–27) – 16 of 42 badge readings, with the highest badge reading exceeding the reconstructed mean dose of 0.033 rem by a factor of about 10;
- USS COCOPA (May 1–7) – at least four of 11 badge readings, with the highest badge reading exceeding the reconstructed mean dose of 0.22 rem by a factor of about 4;
- USS COCOPA (May 8–18) – at least nine of 12 badge readings, with the highest badge reading exceeding the reconstructed mean dose of 0.07 rem by a factor of about 13;
- USS MOLALA (April 12 – May 2) – at least 23 of 57 badge readings, with the highest badge reading exceeding the reconstructed mean dose of 0.14 rem by a factor of about 9;
- USS MOLALA (May 4–7) – about eight of 82 badge readings, with the highest badge reading exceeding the reconstructed mean dose of 0.17 rem by a factor of about 4.5.

The extent to which the highest film badge reading exceeds the reconstructed mean dose by more than a factor of three tends to decrease as the reconstructed mean dose increases. In the two cases on the USS ESTES, where reconstructed mean doses are the highest, fewer than 5% of all unadjusted badge readings would exceed the reconstructed mean dose by more than a factor of three if the highest badge readings apply to members of a decontamination crew.

When the bias factor of 1.3 in film badge readings at this operation is taken into account, adjusted badge readings that exceed the reconstructed mean dose by more than a factor of three in the eight cases listed above are summarized as follows:

- USS ESTES (February 28 – March 9) – Two of 49 adjusted badge readings (< 5%) exceed the reconstructed mean dose for an average crew member by more than a factor of three, and no adjusted badge readings exceed the reconstructed mean dose for members of a decontamination crew by more than a factor of three.
- USS ESTES (May 4–14) – About 43 of 52 adjusted badge readings (83%) exceed the reconstructed mean dose by more than a factor of three. To obtain an upper bound that

[36] Film badge readings in NuTRIS indicate that only one set of badge readings that cover the entire period of the operation exceeds three times the reconstructed mean dose of 2.21 rem for members of a decontamination crew.

exceeds at least 95% of all adjusted badge readings, an upper bound factor of about 10 is required.

- USS ESTES (February 28 – May 14) – No more than one of 39 adjusted badge readings (< 5%) exceeds the reconstructed mean dose for an average crew member by more than a factor of three, and no adjusted badge readings exceed the reconstructed mean dose for members of a decontamination crew by more than a factor of three.
- USS RECLAIMER (April 20–27) – About six of 42 adjusted badge readings (14%) exceed the reconstructed mean dose by more than a factor of three. To obtain an upper bound that exceeds at least 95% of all adjusted badge readings, an upper bound factor of about 5 is required.
- USS COCOPA (May 1–7) – Two of 11 adjusted badge readings (18%) exceed the reconstructed mean dose by more than a factor of three. To obtain an upper bound that exceeds at least 95% of all adjusted badge readings, an upper bound factor of about 3.3 is required.
- USS COCOPA (May 8–18) – At least nine of 12 adjusted badge readings (75%) exceed the reconstructed mean dose by more than a factor of three. To obtain an upper bound that exceeds at least 95% of all adjusted badge readings, an upper bound factor of about 8 is required.
- USS MOLALA (April 12 – May 2) – About 20 of 57 adjusted badge readings (35%) exceed the reconstructed mean dose by more than a factor of three. To obtain an upper bound that exceeds at least 95% of all adjusted badge readings, an upper bound factor of about 5 is required.
- USS MOLALA (May 4–7) – About four of 82 adjusted badge readings (< 5%) exceed the reconstructed mean dose by more than a factor of three.

Thus, use of a 3X upper bound factor is adequate in the first and third cases on the USS ESTES and the second case on the USS MOLALA but is inadequate in the other five cases. In those five cases, the required upper bound factor ranges from slightly greater than 3 to about 10.

**11.1.1.2** *Consideration of Film Badge Readings in NuTRIS.* Comparisons of reconstructed doses with film badge readings on ships presented in the previous section are based

on badge readings summarized in histograms by Thomas et al. (1984; 1991). We also investigated whether NuTRIS gives additional badge readings for participants on ships that could be compared with reconstructed doses.

An important characteristic of data in NuTRIS for participants on ships at Operation CASTLE is that the same badge reading, with the same badge number, often is assigned to several individuals during a given time period. This indicates that NuTRIS does not distinguish between doses to participants who were issued film badges and doses to unbadged participants in a defined cohort. Given this limitation, the following discussion of film badge readings in NuTRIS for participants on ships focuses on the number of distinct readings at different doses, not the total number of doses that are assigned on the basis of badge readings.

We first considered cases discussed in the previous section where Thomas et al. (1984; 1991) compared film badge readings with reconstructed doses. The primary purpose was to investigate whether NuTRIS gives additional badge readings not summarized in histograms in the published reports that exceed a reconstructed mean dose by more than a factor of three. No such badge readings are given in NuTRIS in cases of exposure on the USS ESTES, PHILIP, and SIOUX that were considered by Thomas et al. (1984). However, NuTRIS gives additional high badge readings in some cases that were considered by Thomas et al. (1991), including badge readings that exceed the highest readings shown in histograms in cases of exposure on the USS RECLAIMER (April 28 – May 3), USS COCOPA (May 1–7 and May 8–18), USS MENDER (May 1–10), and USS MOLALA (February 28 – March 5, April 12 – May 2, May 4–7, and May 8–16). The number of distinct high badge readings in NuTRIS in these cases ranges from one to five.

Most of the higher badge readings noted above were reported by Thomas et al. (1991) but were not included in comparisons with reconstructed doses. Some of those readings were excluded on the grounds that they represent exposures during special operations, such as retrieval and handling of contaminated instruments or mines in Bikini Lagoon, and other readings were excluded on the grounds that they are much higher than readings that apply to typical crew members. Since only a few higher badge readings in NuTRIS were not included in comparisons with reconstructed doses by Thomas et al. (1991) and it is questionable whether those badge readings apply to typical crew members, the additional badge readings are not taken into account in evaluating the adequacy of a 3X upper bound factor on ships at this operation. However, the

higher badge readings in NuTRIS raise questions about whether all relevant badge readings were included in comparisons with reconstructed doses by Thomas et al. (1991).

We then considered cases where Thomas et al. (1984) did not provide comparisons of reconstructed doses on ships with film badge readings. As noted in the previous section, Thomas et al. (1984) provided comparisons on only three of the 16 ships (the USS ESTES, PHILIP, and SIOUX) where dose reconstructions were performed; available badge readings on those ships were judged sufficient to allow meaningful comparisons. We investigated whether badge readings in NuTRIS for participants on the other 13 ships could be compared with reconstructed doses given by Thomas et al. (1984). On all ships except the USS LST-825 and LST-975, where NuTRIS does not give any badge readings, NuTRIS gives a substantial number of badge readings for specified time periods that are sufficiently long that the readings may not apply to mission badges. Comparisons of distinct badge readings with reconstructed mean doses in cases where at least five distinct readings are given in NuTRIS are summarized as follows:[37]

USS APACHE –

February 28 – April 4 –

– Reconstructed mean dose, 0.96 rem

– Range of film badge readings, 0.075–0.795 rem (12 readings)

March 12 – May 8 –

– Reconstructed mean dose, 0.87 rem

– Range of film badge readings, 0.04–1.2 rem (10 readings)

April 14 – May 8 –

– Reconstructed mean dose, 0.17 rem

– Range of film badge readings, 0.05–0.44 rem (11 readings)

[37] In cases where NuTRIS gives hundreds of film badge readings, only a representative sample of badge readings was used to estimate the range of badge readings and the total number of distinct readings. These cases include badge readings for participants on the USS BAIROKO, BELLE GROVE, CURTISS, EPPERSON, NICHOLAS, and RENSHAW.

USS BAIROKO –

February 28 – March 11 –

- Reconstructed mean dose, 1.89 rem
- Range of film badge readings, 0.15–1.67 and 4.4 rem (35 readings)

March 11 – April 29 –

- Reconstructed mean dose, 0.70 rem
- Range of film badge readings, 0–0.45 and 1.695 rem (14 readings)

April 5–29 –

- Reconstructed mean dose, 0.16 rem
- Range of film badge readings, 0.02–0.29 rem (13 readings)

May 1–15 –

- Reconstructed mean dose, 0.14 rem
- Range of film badge readings, 0.05–0.335 rem (11 readings)

May 4–15 –

- Reconstructed mean dose, 0.11 rem
- Range of film badge readings, 0.12–0.435 rem (14 readings)

USS BELLE GROVE –

February 28 – March 6 –

- Reconstructed mean dose, 1.01 rem
- Range of film badge readings, 0.45–1.88 rem (19 readings)

March 6 – April 12 –

- Reconstructed mean dose, 0.68 rem
- Range of film badge readings, 0.20–0.94 rem (24 readings)

April 13–27 –

- Reconstructed mean dose, 0.068 rem
- Range of film badge readings, 0–0.10 rem (5 readings)

April 27 – May 11 –

- Reconstructed mean dose, 0.14 rem
- Range of film badge readings, 0.02–0.31 and 1.05 rem (16 readings)

USS CURTISS –

February 28 – March 6 –

- Reconstructed mean dose, 0.31 rem
- Range of film badge readings, 0–0.47 rem (17 readings)

March 8 – May 1 –

- Reconstructed mean dose, 0.14 rem
- Range of film badge readings, 0–0.60 rem (13 readings)

USS EPPERSON –

March 9–30 –

- Reconstructed mean dose, 0.25 rem
- Range of film badge readings, 0.05–0.83 rem (16 readings)

March 31 – May 5 –

- Reconstructed mean dose, 0.08 rem
- Range of film badge readings, 0–0.11 rem (5 readings)

May 5–14 –

- Reconstructed mean dose, 0.009 rem
- Range of film badge readings, 0.015–0.20 rem (7 readings)

USS FRED C. AINSWORTH –

March 1–7 –

- Reconstructed mean dose, 0.35 rem
- Range of film badge readings, 0.02–0.25 rem (10 readings)

USS GYPSY –

March 1–7 –

- Reconstructed mean dose, 1.58 rem
- Range of film badge readings, 1.0–3.1 rem (8 readings)

USS LST-551 –

February 28 – March 6 –

- Reconstructed mean dose, 0.19 rem
- Range of film badge readings, 0.04–0.11, 0.83, and 1.05 rem (9 readings)

April 19 – May 16 –

- Reconstructed mean dose, 0.076 rem
- Range of film badge readings, 0.215–0.375 rem (8 readings)

USS LST-762 –

March 10–16 –

- Reconstructed mean dose, 0.048 rem
- Range of film badge readings, 0.13–0.43 rem (8 readings)

USS NICHOLAS –

March 19 – April 2 –

- Reconstructed mean dose, 0.19 rem
- Range of film badge readings, 0–0.355 rem (11 readings)

May 4–14 –

- Reconstructed mean dose, 0.055 rem
- Range of film badge readings, 0.085–0.29 rem (9 readings)

USS RENSHAW –

March 1–9 –

- Reconstructed mean dose, 0.15 rem
- Range of film badge readings, 0.10–0.905 rem (19 readings)

March 10 – April 29 –

- Reconstructed mean dose, 0.36 rem
- Range of film badge readings, 0–0.625 rem (19 readings)

April 29 – May 14 –

- Reconstructed mean dose, 0.28 rem
- Range of film badge readings, 0.13–0.35 rem (9 readings)

In several cases, exposure rates were not measured on a ship, and reconstructed doses were based partly on measurements on Enewetak Atoll. These cases include exposures on the USS EPPERSON during the last period, the USS LST-551 during both periods, the USS LST-762, the USS NICHOLAS during the first period, and the USS RENSHAW during the first period.

Of the 27 cases summarized above, there are six cases where use of a 3X upper bound factor on the reconstructed mean dose does not appear to give an upper bound that exceeds at least 95% of all distinct badge readings when the bias factor of 1.3 in badge readings at this operation is taken into account. These cases are summarized as follows:

- USS EPPERSON (May 5–14) – Six of seven adjusted badge readings exceed the reconstructed mean dose of 0.009 rem by more than a factor of three, and the highest adjusted badge reading exceeds the reconstructed mean dose by a factor of 17.
- USS LST-551 (February 28 – March 6) – Two of nine adjusted badge readings exceed the reconstructed mean dose of 0.19 rem by more than a factor of three, and the highest adjusted badge reading exceeds the reconstructed mean dose by a factor of 4.
- USS LST-551 (April 19 – May 16) – Three of eight adjusted badge readings exceed the reconstructed mean dose of 0.076 rem by more than a factor of three, and the highest adjusted badge reading exceeds the reconstructed mean dose by a factor of 4.
- USS LST-762 (March 10–16) – Four of eight adjusted badge readings exceed the reconstructed mean dose of 0.048 rem by more than a factor of three, and the highest adjusted badge reading exceeds the reconstructed mean dose by a factor of 7.
- USS NICHOLAS (May 4–14) – One of nine adjusted badge readings exceeds the reconstructed mean dose of 0.055 rem by a factor of 4.
- USS RENSHAW (March 1–9) – Two of 19 adjusted badge readings exceed the reconstructed mean dose of 0.15 rem by more than a factor of three, and the highest adjusted badge reading exceeds the reconstructed mean dose by a factor of 5.

In all these cases, reconstructed mean doses and film badge readings tend to be lower than in the other cases where use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all badge readings in NuTRIS. When the reconstructed mean dose is at least

0.31 rem, the highest badge reading in NuTRIS exceeds the reconstructed mean dose by less than a factor of three.[38]

Of the six cases summarized above, perhaps the clearest case where use of a 3X upper bound factor appears to be inadequate involves exposure on the USS RENSHAW during the period March 1–9. There is a substantial number of distinct badge readings, and the highest readings do not appear to be outliers compared with other higher readings that exceed the reconstructed mean dose by less than a factor of three. The reconstructed dose in this case was based on measured exposure rates on residence islands at Enewetak Atoll. In the other five cases, either there are relatively few badge readings (all five cases have fewer than 10 distinct readings), the highest adjusted badge readings in three cases do not exceed the reconstructed mean dose by much more than a factor of three, or it is possible that the highest badge readings are outliers that do not apply to typical crew members (on the LST-551 during the period February 28 – March 6, the two highest badge readings are at least a factor of 7.5 and 9.5 higher than any other reading).

Thomas et al. (1984) did not provide an explanation of why film badge readings on the 11 ships discussed above were not reported and compared with reconstructed doses, other than a statement which implied that available badge readings were insufficient to allow meaningful comparisons. The number of badge readings does not appear to be an important limitation, because the number of readings in NuTRIS in many of those cases is comparable to or greater than the number of readings on the USS SIOUX that were reported by Thomas et al. (1984) and compared with reconstructed doses. Given the doubt about whether film badge readings in NuTRIS that were not reported by Thomas et al. (1984) can be compared with reconstructed doses on the 11 ships, these comparisons are not used in our evaluation of the adequacy of a 3X upper bound factor on ships. However, badge readings on the 11 ships given in NuTRIS raise questions about whether all relevant badge readings were taken into account in comparisons with reconstructed doses on all ships that were considered by Thomas et al. (1984).

[38] It also is possible that more than one badge reading at the same dose given in NuTRIS represents readings of more than one badge, and this possibility presumably is less likely at higher badge readings. If this situation occurred in any cases summarized above, the number of badge readings that exceed the reconstructed mean dose by more than a factor of three would be reduced. However, we cannot evaluate this possibility on the basis of information in NuTRIS.

### 11.1.2 *Exposures on Residence Islands*

Thomas et al. (1984) gives reconstructed mean doses on residence islands during the period March 1 – May 31 of 1.09 rem at Enewetak Atoll and 0.32 rem at Kwajalein Atoll. In a subsequent dose reconstruction at Kwajalein Atoll in an SAIC memorandum (Raine, 1998), the reconstructed mean dose was increased to 0.73 rem. Film badge readings for participants on residence islands during that period were not reported by Thomas et al. (1984) or Raine (1998).

Limited information on film badge readings at Enewetak Atoll is given by Martin and Rowland (1982). During the period following Shot BRAVO on March 1, readings of two badges that were placed at different locations are 0.075 and 0.11 R; the period of exposure was not specified. These badge readings are less than the reconstructed mean dose during periods ending March 2 or later (Thomas et al., 1984). During the period March 24 – April 9, readings of ten film badges that were placed at different locations range from 0.265 to 1.57 R. The reconstructed mean dose during that period is 0.51 rem (Thomas et al., 1984), and the highest badge reading exceeds the reconstructed mean dose by a factor of about three.

NuTRIS gives film badge readings for many participants in various units that were stationed on Enewetak Atoll. Those badge readings cover many time periods, ranging from a day or two to the entire period of the operation. Many badges readings in NuTRIS, especially badges that were issued for periods of a few days or less, presumably apply to mission badges that recorded exposures at locations away from Enewetak Atoll. In addition, badges that were issued for longer time periods may have recorded exposures at other locations as well as at Enewetak Atoll. Given the doubt about whether film badges with readings in NuTRIS recorded exposures at Enewetak Atoll only, comparisons of those badge readings with reconstructed doses given by Thomas et al. (1984) may not be meaningful, even in cases where badges were issued for an extended period. A similar situation occurs with film badge readings in NuTRIS for members of a plane patrol unit that was stationed at Kwajalein Atoll.

### 11.1.3 *Exposures on Rongerik Atoll*

Participants who were stationed on Rongerik Atoll were exposed to high levels of fallout from Shot BRAVO on March 1–2. External doses to specific individuals were reconstructed by

Goetz et al. (1987) on the basis of measured exposure rates at outdoor and indoor locations on March 10, assumptions about the variation in exposure rates over time, as estimated from data obtained at Bikini Atoll, and information about locations and times of exposure of specific individuals, as obtained from interviews with participants after they were evacuated. Reconstructed doses range from 35 to 51 rem, depending on when evacuation occurred and fraction of the time an individual spent inside various structures on the atoll.

Available film badge readings also were considered by Goetz et al. (1987). However, interpretation of those readings was not straightforward when badges were not worn continuously by specific individuals but were often placed at certain indoor or outdoor locations. In addition, there were inconsistencies among the sources of information on badge readings concerning assignment of specific badges and in some of the reported readings.

Film badge readings range from 37.5 to 98 rem. The highest reading applies to a badge that was mounted outdoors on a tent pole during the entire period of exposure, and many lower readings apply to badges that were stored in a refrigerator. By taking into account the assumed activity scenarios for exposed individuals and protection factors during indoor exposures, Goetz et al. (1987) concluded that reconstructed doses were about 10–14% higher than comparable film badge readings. Thus, even though there were difficulties in interpreting available information on badge readings, reconstructed doses are in good agreement with badge readings in this case of unusually high exposure. This is a noteworthy result when reconstructed doses could not be based on measured exposure rates at the time of exposure.

### 11.2 SAIC Memoranda

Many memoranda that addressed exposures of particular units during Operation CASTLE that were not considered in the unit dose reconstructions discussed in Section 11.1 were prepared by SAIC (Thomas and Klemm, 1987, 1992; Goetz, 1989; Klemm, 1989; Thomas, 1990, 1991, 1993a,f; Martinez, 1994, 1995a–k,m–u, 1996a,b, 2001; Ortlieb, 1995a,b; Cockayne, 1997a,b; Raine, 1998, 2000a,b). Earlier memoranda (Thomas et al., 1982; Goetz, 1982; Gminder, 1982; Thomas, 1983) presumably were superseded by published unit dose reconstructions discussed in Section 11.1. Only three memoranda give additional information on comparisons of reconstructed external gamma doses with film badge readings.

Thomas and Klemm (1987) addressed exposure of crew members on the USS LST-1157. Comparisons of reconstructed mean doses with distinct readings of permanent film badges that apply during extended periods of exposure are summarized as follows:

USS LST-1157 –

April 5 – May 1 –

- Reconstructed mean dose, 0.155 rem
- Range of film badge readings, 0–0.14 rem (11 readings)

May 2–15 –

- Reconstructed mean dose, 0.313 rem
- Range of film badge readings, 0.125–0.76 and 1.57 rem (14 readings)

In the first time period, the reconstructed mean dose is higher than all badge readings. In the second time period, only one of the 14 distinct badge readings exceeds the reconstructed mean dose by more than a factor of three. When the bias factor of 1.3 in film badges at this operation is taken into account, the highest adjusted badge reading in the second period exceeds the reconstructed mean dose by a factor of 4. The reconstructed dose during the first period was based on measured exposure rates on the ship, whereas the reconstructed dose during the second period was based on measurements on Parry Island.

Raine (1998) addressed exposure of participants who were stationed on Majuro Atoll; this dose reconstruction superseded a previous dose reconstruction by Thomas (1990). A comparison of the reconstructed mean dose given by Raine (1998) with film badge readings for a particular time period reported by Thomas (1990) is summarized as follows:

Majuro Atoll –

March 25 – April 20 –

- Reconstructed mean dose, 0.11 rem
- Range of film badge readings, 0–0.47 rem (14 total badges)

Only one badge reading exceeds the reconstructed mean dose by more than a factor of three. Furthermore, when the bias factor of 1.3 in film badge readings is taken into account, the highest badge reading exceeds the reconstructed mean dose by a factor of 3.3, which is only marginally

greater than 3. Thus, a possible inadequacy of a 3X upper bound factor probably is not significant in this case.

### 11.3 Summary of Analysis

Published unit dose reconstructions and an SAIC memorandum provide many comparisons of reconstructed mean doses from external exposure to residual gamma radiation at Operation CASTLE with film badge readings in cases of exposure to fallout on ships. However, except for exposures on Rongerik Atoll to high levels of fallout from Shot BRAVO, only limited information that can be used to compare reconstructed mean doses with film badge readings on residence islands and other atolls is available in published reports and SAIC memoranda.

Reconstructed mean doses on ships were compared with film badge readings reported in published unit dose reconstructions and an SAIC memorandum in a total of 37 cases. When the bias factor of 1.3 in badge readings at this operation is taken into account, these comparisons are summarized as follows:

- In 32 of the 37 cases on ships, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds at least 95% of all film badge readings or exceeds all but one of the badge readings when there were relatively few readings. In three of these cases, there are fewer than five badge readings, and comparisons with reconstructed doses in those cases may not be meaningful.
- In 5 of the 37 cases on ships (one case each on the USS ESTES, RECLAIMER, and MOLALA and two cases on the USS COCOPA), use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that does not exceed at least 95% of all film badge readings. To give upper bounds of reconstructed doses that exceed at least 95% of all film badge readings or all but one badge reading when there are relatively few readings, the required upper bound factor is about 10 on the USS ESTES during the period May 4–14, 5 on the USS RECLAIMER during the period April 20–27, 3.3 on the USS COCOPA during the period May 1–7, 8 on the USS COCOPA during the period May 8–18, and 5 on the USS MOLALA during the period April 12 – May 2.

In all five cases where use of a 3X upper bound factor is inadequate, reconstructed mean doses and film badge readings tend to be low compared with reconstructed mean doses and badge readings in the 32 cases where use of a 3X upper bound factor is adequate. Reconstructed mean doses in the five cases are 0.22 rem or less and almost all badge readings are 1 rem or less, whereas in several cases where use of a 3X upper bound factor is adequate, reconstructed mean doses are above 1 rem and the highest badge readings are about 4 rem or higher. We also noted that the required upper bound factor of 3.3 in one case on the USS COCOPA is only slightly greater than 3. This comparison probably does not indicate a significant discrepancy between the reconstructed dose and film badge readings. In four of the five cases, reconstructed doses were based on measured exposure rates on that ship; only on the USS RECLAIMER was the reconstructed dose based on measured exposure rates on nearby ships or islands.

Limited information that can be used to compare reconstructed mean doses on Enewetak, Kwajalein, and Majuro Atolls with film badge readings suggests that use of a 3X upper bound factor gives upper bounds that exceed doses that were received by at least 95% of all participants at those locations. However, this conclusion may not be definitive when very few comparisons could be made on the basis of film badge readings in published reports or SAIC memoranda. In the case of very high exposures on Rongerik Atoll, however, reconstructed doses are in good agreement with film badge readings.

Extensive film badge readings for participants on ships or residence islands given in NuTRIS also were investigated. Badge readings in NuTRIS were not used in evaluating the adequacy of a 3X upper bound factor in estimating upper bounds of reconstructed doses, mainly because there is doubt about whether badge readings in NuTRIS that were not given in published reports or SAIC memoranda apply to conditions of exposure that were taken into account in dose reconstructions. However, the additional badge readings in NuTRIS raise questions about whether an analysis based only on badge readings that were given in published reports or SAIC memoranda provides an accurate accounting of cases where use of a 3X upper bound factor is inadequate. This concern seems especially important on 11 ships where film badge readings were not reported by Thomas et al. (1984) and compared with reconstructed doses, even though a substantial number of badge readings are given in NuTRIS, and an explanation for the omission of badge readings in NuTRIS was not provided. If badge readings in NuTRIS are relevant, use of a 3X upper bound factor could be inadequate in six of an additional 27 cases on

ships, including exposures on the USS EPPERSON during the period May 5–14, USS LST-551 during the periods February 28 – March 6 and April 19 – May 16, USS LST-762 during the period March 10–16, USS NICHOLAS during the period May 4–14, and USS RENSHAW during the period March 1–9.

Finally, it is important to emphasize that although use of a 3X upper bound factor was found to be inadequate in a number of cases on ships at Operation CASTLE, these inadequacies probably are mitigated by the use of cohort badges to estimate doses to unbadged participants (Thomas et al., 1984, 1991; DTRA, 2008, Appendix B.5). By use of cohort badging, reconstructed doses that may significantly underestimate doses to participants on ships in some cases generally are not assigned to unbadged participants.

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# 12. OPERATIONS AT PPG – VI.
# OPERATION WIGWAM (1955)

## 12.1 Unit Dose Reconstructions

Operation WIGWAM consisted of a single deep underwater test at a location about 500 miles southwest of San Diego, California. Participants on a few ships, including members of a boat pool, were potentially exposed to fallout from that shot (Weary et al., 1981).

There are no published dose reconstructions for military units at Operation WIGWAM, nor are any unit dose reconstructions given in SAIC memoranda. Therefore, comparisons of reconstructed doses with film badge readings cannot be made. However, since all participants apparently were issued film badges and participants who were located in areas where exposure could have occurred were issued additional badges on a daily basis (Weary et al., 1981), there has been no evident need for unit dose reconstructions to be performed.

## 12.2 Information on Doses to Participants

Information on film badge readings for participants at Operation WIGWAM is summarized by Weary et al. (1981). About 91% of all badges that were issued have a reading below 0.1 rem, in which case a mean dose of zero has been assigned, readings of 3.4% of the badges were unavailable, 5% have a reading that ranges from 0.1 to 0.165 rem, and 0.5% have a reading above 0.165 rem; the highest reading, which applies to a member of an aviation support group, is 0.425 rem. It is thus apparent that doses at this operation generally were low. Distributions of film badge readings on selected ships where there are non-zero readings are summarized in Table 12.1.

An SAIC memorandum (Booker, 1998) indicates that a mean dose and upper bound of zero have been assigned to participants with a film badge reading of zero (i.e., < 0.1 rem), except in cases of exposure on ships where at least 5% of the badge readings exceed the assumed threshold for a non-zero dose of 0.1 rem. In the exceptional cases on ships, an upper bound of 0.1 rem has been assigned to participants with a badge reading of zero; this upper bound applies to members of a boat pool and to personnel on the M/V HORIZON and the USS BOLSTER,

CHANTICLEER, GEORGE EASTMAN, and TAWASA. On the USS WRIGHT, where 36 of 839 badge readings are 0.1 rem or above, an upper bound dose of zero has been assigned to participants with a badge reading of zero on the grounds that less than 5% of the readings exceed 0.1 rem; all non-zero readings on that ship are 0.165 rem or less (Weary et al., 1981).

**Table 12.1.** Distributions of film badge readings for military participants on selected ships at Operation WIGWAM[a]

| Ship | Number of badges[b] | Unavailable badge readings | Readings < 0.1 rem[c] | Readings ≥ 0.1 rem |
|---|---|---|---|---|
| USS GEORGE EASTMAN | 49 | 1 | 42 | 6 |
| USS GRANVILLE S. HALL | 48 | 0 | 47 | 1 |
| M/V HORIZON | 59 | 10 | 18 | 31 |
| Boat pool | 230 | 18 | 181 | 31 |
| USS CHANTICLEER | 96 | 0 | 15 | 81 |
| USS TAWASA | 73 | 0 | 35 | 38 |
| USS BOLSTER | 91 | 0 | 65 | 25 |
| USS WRIGHT | 974 | 45 | 839 | 36 |
| USS FRANK E. EVANS | 269 | 27 | 241 | 1 |
| USS ALFRED A. CUNNINGHAM | 268 | 12 | 252 | 4 |
| USS CURTISS | 573 | 17 | 551 | 5 |
| USS MCKEAN | 256 | 3 | 248 | 5 |
| USS MOUNT MCKINLEY | 552 | 9 | 538 | 5 |

[a] See Table 4-1 and Appendix J, Table J-3 of Weary et al. (1981).

[b] In some cases, reported number of film badges is not equal to sum of the number of badge readings in each category; reasons for these discrepancies are unknown to us.

[c] Dose of zero has been assigned when film badge reading is less than 0.1 rem.

Information in NuTRIS indicates that when a film badge reading is unavailable for a participant on a ship, a non-zero dose that is based on a dose reconstruction is assigned, except on the USS FRANK E. EVANS where there is only one non-zero badge reading. Although the

basis for a reconstructed dose is not indicated in NuTRIS and we are not aware of any SAIC memoranda that discuss dose reconstructions, non-zero reconstructed doses in NuTRIS range from 0.032 rem on the USS MCKEAN to 0.282 rem on the M/V HORIZON. In a few cases, including on the M/V HORIZON and USS WRIGHT, the reconstructed dose is substantially above the mean of all non-zero badge readings given by Weary et al. (1981).

### 12.3 Discussion of Assigned Doses

Although the adequacy of a 3X upper bound factor cannot be evaluated in cases of exposure at Operation WIGWAM, because of the absence of dose reconstructions in published reports or SAIC memoranda, we believe that three observations are warranted on the basis of available information on doses that have been assigned to participants at this operation in cases where a badge reading is unavailable or a badge reading is less than 0.1 rem.

First, in cases where a badge reading is unavailable and a reconstructed dose is given in NuTRIS, use of a 3X upper bound factor on the reconstructed dose gives an upper bound that probably exceeds at least 95% of all badge readings on all ships.

Second, in cases where an upper bound dose of 0.1 rem has been assigned to participants with a badge reading of zero, that dose equals or exceeds at least 95% of all badge readings on some ships but not on others. However, if a mean dose of 0.1 rem, rather than zero, were assigned to those participants, use of a 3X upper bound factor on that mean dose would give an upper bound that exceeds at least 95% of all badge readings on all ships. Use of a 3X upper bound factor also should be adequate if a mean dose equal to a nominal minimum detectable dose of 0.050 rem (see Section 1.4) were assigned.

Finally, in cases where an upper bound dose of zero has been assigned to participants with a badge reading of zero on the grounds that less than 5% of the badge readings on a ship exceed the threshold for a non-zero dose of 0.1 rem, this upper bound may be justifiable when there are very few non-zero badge readings (e.g., on the USS FRANK E. EVANS). However, we believe that assigning an upper bound dose of zero is difficult to justify when a substantial number of badge readings, albeit less than 5%, are above 0.1 rem (e.g., on the USS WRIGHT), because assigning an upper bound dose of zero does not give a participant the benefit of the doubt in estimating dose. We believe that a more justifiable approach would be to assume a

mean dose equal to the nominal minimum detectable dose of 0.050 rem. If such a mean dose were assigned, use of a 3X upper bound factor should be adequate in all cases.

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# 13. OPERATIONS AT PPG – VII.
# OPERATION REDWING (1956)

## 13.1 Published Unit Dose Reconstructions

There are no published dose reconstructions for military units at Operation REDWING, which consisted of 17 tests that were conducted at Enewetak and Bikini Atolls between May 5 and July 22, 1956. However, as discussed in Section 13.3, several dose reconstructions that apply to participants on residence islands or ships are given in SAIC memoranda.

## 13.2 Discussion of Film Badge Dosimetry

A comprehensive film badge dosimetry program was conducted during Operation REDWING in an effort to provide complete information on external gamma exposures for each participant (Bruce-Henderson et al., 1982; McRaney, 1992, 1993). A permanent badge, which was to be worn at all times, was issued to each participant who entered a test area. In addition, mission badges were issued to participants who were involved in special activities with a known potential for radiation exposure, such as cloud sampling and recovery of equipment from contaminated areas; these badges were worn only for the duration of a special activity.

Most permanent badges that were worn for periods of about four weeks or more during the operation were found to be damaged due to effects of high heat and humidity, and damaged film generally was difficult to read (Bruce-Henderson et al., 1982; McRaney, 1992, 1993; NRC, 1989). Damaged film often was badly watermarked and showed evidence of severe light leaks. Since environmental damage resulted in increases in optical density on the film that also would have been caused by exposure to radiation, damaged film would indicate an exposure higher than the actual exposure if effects of environmental damage were not taken into account. McRaney (1993) estimated that the increase in optical density on damaged film was equivalent to an exposure of several hundred mrem.

Potential overestimates of exposure by several hundred mrem due to environmental damage impact an ability to estimate doses reliably on the basis of film badge readings, and they limit the extent to which badge readings can be compared with reconstructed doses for the

purpose of evaluating the adequacy of applying a 3X upper bound factor to reconstructed mean doses. For example, a review and evaluation of film badges for participants on several ships (McRaney, 1993) discussed in the following section indicated that, in the worst cases, only a small fraction of badge readings above 0.1 rem were considered to be reliable. The fraction of reliable readings was judged to approach 50% in the best cases.

As a result of problems with permanent film badges at this operation, SAIC analysts generally evaluate the condition of film badges and the validity of readings on a case-by-case basis (DTRA, 2008; Standard Method ED01, Section 5.1.1.2). Reconstructed doses are used in lieu of badge readings when readings are judged to be questionable. However, readings of badges judged to be questionable may be used to estimate upper bounds of doses when a participant's exposure scenario is highly uncertain.

### 13.3 SAIC Memoranda

Many memoranda that addressed exposures of particular units during Operation REDWING were prepared by SAIC (Gminder, 1984; Thomas, 1984a,b, 1985a–c, 1987, 1991, 1992; Goetz, 1985, 1989; McRaney, 1992, 1993; Klemm, 1994; Martinez, 1994a–c, 1995a–d, 1996a–k,m–q, 1997; Stiver, 2004). As described below, four of those memoranda give information on comparisons of reconstructed external gamma doses with film badge readings.

Goetz (1985) noted that reconstructed doses for participants in Task Group 7.2 on Enewetak Island during the period August 7 – September 30 agree very well with film badge readings. Doses during that period were due primarily to fallout from Shot TEWA on July 21. Reconstructed doses for participants who spent most of the time indoors range from 0.44 to 0.954 rem, with an average of 0.70 rem, and reconstructed doses for participants who spent most of the time outdoors range from 0.585 to 1.275 rem, with an average of 0.93 rem. However, badge readings were not reported by Goetz (1985), and NuTRIS does not give any badge readings for participants in this unit during this time period. Therefore, we could not evaluate the comparison of reconstructed doses with film badge readings discussed by Goetz (1985).

Thomas (1985c) noted that reconstructed doses for participants in Task Group 7.2 on Enewetak Island and in Task Group 7.1 and Headquarters staff of Joint Task Force 7 on Parry Island during the period April 13 – August 6 agree well with means of film badge readings for

that period, provided it is assumed that decontamination activities were carried out on Parry Island, as indicated in radiological safety reports, but were not carried out on Enewetak Island even though levels of contamination should have been similar on the two islands at Enewetak Atoll.[39] Doses during that period were due primarily to fallout from Shot TEWA. Means of badge readings given by Thomas (1985c) are 3.22 rem for Task Group 7.2 on Enewetak Island and 2.43 rem and 2.52 rem for Task Group 7.1 and Headquarters staff of Joint Task Force 7, respectively, on Parry Island. Reconstructed doses for participants who spent most of the time indoors or outdoors on either island are 2.09 and 2.78 rem, respectively, if decontamination is assumed and 2.74 and 3.65 rem, respectively, if decontamination is not assumed. NuTRIS does not give any badge readings for participants on Enewetak Island that cover the time period of interest. On Parry Island, NuTRIS gives badge readings for 11 participants during this period; the sum of readings for those participants ranges from 1.41 to 5.45 rem.

It should be noted that the assumption by Thomas (1985c) that decontamination did not occur on Enewetak Island was based on the better agreement between reconstructed doses and the mean film badge reading compared with the extent of agreement when decontamination was assumed. A comparison based on that assumption does not provide an independent test of the validity of reconstructed doses on Enewetak Island. However, even if the assumption that decontamination did not occur is incorrect, the mean film badge reading on Enewetak Island does not exceed reconstructed doses by more than about 15–55%. In addition, on the basis of limited information on film badge readings in NuTRIS, it appears that the highest total doses based on those readings are within a factor of three of the lowest reconstructed dose without accounting for the bias of a factor of 1.3 in film badge readings at this operation (see Table 1.1).

McRaney (1992, 1993) compared reconstructed doses with film badge readings for participants on some ships as part of an evaluation of the extent of environmental damage to film at Operation REDWING. These comparisons are summarized as follows:

- On the USNS FRED C. AINSWORTH during the period June 22 – July 23, the average dose indicated by 80 badges with undamaged film (44% of all badges included in the evaluation) is about 0.13 rem, and the highest badge reading is 0.38 rem. The

[39] Radiological safety reports apparently did not mention whether decontamination activities were carried out on Enewetak Island. Previous dose reconstructions for participants on Enewetak Island (Thomas, 1984a,b) assumed that decontamination activities were carried out there.

reconstructed mean dose is about 0.22 rem.[40] Several badges judged to be damaged have readings between 0.4 and 0.7 rem. During the period April 28 – June 22, only five films (3% of all evaluated badges) were judged to be undamaged; four readings are 0.13 rem or less, and one reading is 0.30 rem. The reconstructed mean dose is about 0.11 rem. Many badges judged to be damaged have readings between 0.4 and 1.6 rem. In both time periods, the highest readings of undamaged badges are within a factor of three of the reconstructed mean dose without accounting for the bias factor of 1.3 in badge readings. Reconstructed doses were based on comprehensive survey data on this ship.

- On the USS JAMES E. KYES during the period April 23 – June 21, only three of 212 film badge readings included in the evaluation were judged to be reliable; those readings are between 0.04 and 0.11 rem. The reconstructed mean dose is less than 0.01 rem. When the bias factor of 1.3 in badge readings is taken into account, the highest reliable reading exceeds the reconstructed mean dose by more than a factor of 8. Questionable badge readings range from less than 0.1 to greater than 1.6 rem. During the period June 21 – July 23, 60 of the 207 evaluated film badge readings were judged to be reliable; 85% of those readings are less than 0.2 rem, and the highest reading is 0.28 rem. The reconstructed mean dose, as given by Thomas (1992), is about 0.1 rem. The highest reliable badge reading is within a factor of three of the reconstructed mean dose without accounting for the bias in badge readings. Questionable badges have readings between 0.1 and 0.9 rem. Reconstructed doses were based on survey data on nearby ships and islands and knowledge of ship locations.
- On the USS SHELTON during the period April 20 – June 12, 15% of the film badge readings included in the evaluation were judged to be reliable; most of those readings are less than 0.1 rem, eight readings (about 4% of the total and 30% of the reliable readings) are greater than 0.1 rem, and the highest reading is 0.315 rem. The reconstructed mean dose is less than 0.01 rem. When the bias factor of 1.3 in badge readings is taken into account, the eight reliable badge readings above 0.1 rem exceed the reconstructed mean dose by more than a factor of 8. To exceed at least 95% of all reliable badge readings, an

[40] This reconstructed dose applies to crew members who remained on board the ship during the entire period. The reconstructed mean dose for crew members who went on liberty to Enewetak Island on July 22 is 0.25 rem. This additional dose could account for some of the higher readings of undamaged film badges (McRaney, 1993).

upper bound factor of at least 20 probably is required. Questionable badge readings range from less than 0.1 to 1.5 rem. During the period June 12 – July 24, evaluated film badge readings judged to be reliable are between 0.4 and 1.1 rem. McRaney (1993) compared these readings with a "threshold dose" of 0.48 rem, which was calculated on the basis of the upper bound of the reconstructed dose for a typical crew member and uncertainties in badge readings.[41] On the basis of information available to us, it is difficult to compare film badge readings with a reconstructed mean dose during this period. Questionable badge readings range from 0.5 to greater than 1.6 rem. Doses during this period were attributed to relatively high levels of fallout from Shot TEWA while the ship was anchored at Enewetak Atoll. Reconstructed doses were based on survey data on nearby ships and islands and knowledge of ship locations.

- On the USS BADOENG STRAIT during the period April 19, 20 – June 13, 14, only one film badge reading included in the evaluation was judged to be reliable; that reading is between 0.2 and 0.3 rem. The "threshold dose" calculated by McRaney (1993) is 0.22 rem.[42] Questionable badge readings range from 0.2 to greater than 1.6 rem. During the period June 13, 14 – July 26, the few evaluated film badge readings judged to be reliable are between 0.1 and 0.3 rem. Neither a "threshold dose" nor a reconstructed mean dose was given by McRaney (1993); the reconstructed mean dose given by Thomas (1991) is 0.22 rem. Questionable badge readings range from 0.2 to 1.6 rem. In both time periods, the highest reliable badge reading probably is within a factor of three of the reconstructed mean dose without accounting for the bias in badge readings. McRaney (1993) did not describe the basis for dose reconstructions.
- On the USS ESTES during the period April 23–25 – June 25–28, only two film badge readings included in the evaluation were judged to be reliable; those readings are between 0.2 and 0.3 rem. The "threshold dose" calculated by McRaney (1993) is 0.22 rem.[43]

[41] A reconstructed mean dose is not given by McRaney (1993), nor is a table of daily doses on this ship given in other SAIC memoranda (Thomas, 1991, 1992; Martinez, 1994a,b). The reconstructed mean dose presumably is at least 20% less than the threshold dose as defined by McRaney (1993).

[42] The threshold dose given by McRaney (1993) appears to be inconsistent with a higher reconstructed mean dose for this period of 0.27 rem given by Thomas (1991).

[43] The threshold dose given by McRaney (1993) appears to be inconsistent with a higher reconstructed mean dose for this period of about 0.27 rem given by Thomas (1992).

Questionable badge readings range from 0.2 to greater than 1.6 rem. During the period June 25–28 – July 25, only about four evaluated film badge readings were judged to be reliable; those readings are between 0.1 and 0.2 rem. Neither a "threshold dose" nor a reconstructed mean dose was given by McRaney (1993); the reconstructed mean dose given by Thomas (1992) is 0.14 rem. Questionable badge readings range from 0.1 to 1.1 rem. In both time periods, the highest reliable badge reading probably is within a factor of three of the reconstructed mean dose without accounting for the bias in badge readings. McRaney (1993) did not describe the basis for dose reconstructions.

- On the USS ABNAKI during the period April 24 – June 18, only one film badge reading included in the evaluation was judged to be reliable; that reading is between 0.6 and 0.7 rem. Neither a "threshold dose" nor a reconstructed mean dose was given by McRaney (1993); the reconstructed mean dose given by Thomas (1991) is 0.63 rem. The one reliable badge reading is within a factor of three of the reconstructed mean dose without accounting for the bias in badge readings. Questionable badge readings range from 0.6 to 1.6 rem. During the period June 20 – July 24, no evaluated film badge readings were judged to be reliable. The reconstructed mean dose given by Thomas (1991) is 0.28 rem. Questionable badge readings range from 0.3 to 0.9 rem. McRaney (1993) did not describe the basis for dose reconstructions.

The analyses by McRaney (1992, 1993) summarized above provide comparisons of reconstructed doses with film badge readings for participants on ships in a total of 11 cases. In eight cases, the highest badge reading among the readings that were judged to be reliable is within a factor of three of the reconstructed mean dose. In two cases on the USS JAMES E. KYES and USS SHELTON during the first time period, the highest badge readings that were judged to be reliable exceed the reconstructed mean dose by nearly an order of magnitude or more when the bias factor of 1.3 in badge readings is taken into account; the reconstructed mean dose in both cases is low (less than 0.01 rem). Possible causes of the highest readings in those two cases were not discussed by McRaney (1993). However, the comparison on the USS JAMES E. KYES during the first time period probably is not meaningful when only three film badge readings were judged to be reliable. On the USS SHELTON during the second time period, a comparison is difficult when only a "threshold dose", which was based in part on the

upper bound of the reconstructed dose, was given by McRaney (1993) and the reconstructed mean dose is not known to us. If the reconstructed mean dose is about 0.3 rem or higher, fewer than 5% of the evaluated film badge readings that were judged to be reliable would exceed the reconstructed mean dose by more than a factor of three when the bias in badge readings is taken into account.

### 13.4 Summary of Analysis

There are no published dose reconstructions for military units at Operation REDWING, and only limited information that can be used to compare reconstructed doses on residence islands or ships with film badge readings is available in SAIC memoranda. The extent to which reconstructed doses and film badge readings can be compared at this operation is inherently limited by the environmental damage to many badges, which resulted in substantial overestimates of dose compared with actual doses received.

In the few cases where reconstructed doses on residence islands are compared with film badge readings in SAIC memoranda, there apparently is good agreement between the two. However, an independent evaluation of the extent of agreement and the adequacy of using a 3X upper bound factor on reconstructed mean doses is somewhat difficult when no information on film badge readings is given in one case and only mean badge readings are given in the other cases. We also noted that only a few film badge readings in one case are given in NuTRIS.

Reconstructed doses were compared with film badge readings on several ships on the basis of information in SAIC memoranda. In nearly all cases where the reconstructed mean dose is at least 0.1 rem, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds at least 95% of all badge readings that were judged to be reliable. There is some doubt about this conclusion in one case where the reconstructed mean dose was not given in an SAIC memorandum, but it appears unlikely that the highest badge reading exceeds the reconstructed mean dose by more than a factor of three when the bias factor of 1.3 in badge readings at this operation is taken into account. In the two cases where the reconstructed mean dose is less than 0.01 rem, the highest badge readings exceed the reconstructed mean dose by nearly a factor of ten or more. However, only one badge reading above 0.1 rem was judged to be reliable in one case, and many more readings above 0.1 rem were judged to be questionable

compared with the few reliable readings in the other case. Therefore, the significance of the few highest badge readings in those two cases is difficult to assess.

In general, we believe that it is difficult to reach firm conclusions about the adequacy of a 3X upper bound factor in reconstructing external gamma doses at Operation REDWING. In addition to the constraint imposed by limited information on comparisons of reconstructed mean doses with film badge readings in SAIC memoranda, these comparisons depend on judgments about the reliability of badge readings, i.e., whether environmental damage precludes a reliable reading of radiation exposure. Given the somewhat subjective nature of those judgments, it is possible that higher badge readings that give reasonably realistic estimates of dose were excluded on the grounds that they were believed to be unreliable. This concern is discussed in a report by the National Research Council (NRC, 2003).

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# 14. OPERATIONS AT PPG – VIII.
# OPERATION HARDTACK I (1958)

## 14.1 Published Unit Dose Reconstructions

There are no published dose reconstructions for military units at Operation HARDTACK I, which consisted of 32 tests that were conducted at Enewetak and Bikini Atolls between May 6 and August 18, 1958, and three high-altitude tests (a balloon shot between Enewetak and Bikini Atolls and two rocket shots at Johnston Island) that were conducted on April 28, July 31, and August 11. However, as discussed in Section 14.3, many dose reconstructions that apply to participants on residence islands or ships are given in SAIC memoranda.

## 14.2 Discussion of Film Badge Dosimetry

A film badge was issued to all participants who entered a test area during Operation HARDTACK I in an effort to provide complete information on external gamma exposures for each participant (Gladeck et al., 1982). In contrast to the experience in using film badges at Operation REDWING (see Section 13.2), film badges that were issued for periods as long as six months did not show indications of significant damage (Gladeck et al., 1982; NRC, 1989), and readings generally have been considered to be reliable indicators of external gamma dose.

## 14.3 SAIC Memoranda

Many memoranda that addressed exposures of particular units during Operation HARDTACK I were prepared by SAIC (Weitz and Thomas, 1985; Thomas, 1987; McRaney, 1989, 1992a,b, 1993a,b, 1995; Weitz 1994, 1995a–k,m–t, 1996a–g, 1997a–c, 1998, 1999a,b; Weitz and McRaney, 1995). Some of those memoranda give information on comparisons of reconstructed external gamma doses with film badge readings. Comparisons on residence islands or ships are discussed separately in the following sections.

### **14.3.1** *Exposures on Residence Islands*

Reconstructed doses for participants in camps on residence islands at Enewetak Atoll (Enewetak, Parry, and Japtan Islands) and Bikini Atoll (Eneu Island) are given by Weitz and Thomas (1985), Thomas (1987), and Weitz (1994; 1995a). Reconstructed doses given by Weitz (1995a) presumably represent current estimates.[44] Reconstructed doses apply to participants who spent most of the time on or near a residence island; they do not apply to participants who engaged in such activities as shot preparation, decontamination of land or equipment, observation of experiments or recovery of experimental equipment on contaminated islands, radiation surveys, or cloud sampling.

Weitz and Thomas (1985) gives film badge readings for participants on Enewetak Atoll that apply to time periods starting in April and ending between the end of May and about August 5; mean badge readings and standard deviations of distributions of badge readings are plotted for 17 cases involving exposure of various subgroups of personnel in a Navy boat pool and boat pool detachment, who were billeted on residence islands or on barges that were docked near residence islands, and Army personnel in Task Group 7.2. The highest mean badge readings and their standard deviations are 2.18 ± 0.25 rem through June 30 for four participants on Japtan Island and about 2.4 ± 0.5 rem through July 12 for six participants in a Navy group. The reconstructed cumulative doses for those two groups given by Weitz (1995a) are 1.47 and 1.52 rem, respectively. Although the two highest mean badge readings are about 50–60% higher than the corresponding reconstructed mean doses, it appears in both cases that use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds all badge readings without accounting for the bias of a factor of 1.5 in film badge readings at this operation (see Table 1.1). Use of a 3X upper bound factor also gives upper bounds that exceed at least

[44] Reconstructed doses at Enewetak Atoll given by Weitz (1995a) are lower than doses given by Weitz and Thomas (1985). Reconstructed cumulative doses during each month through August 1958 given by Weitz (1995a) are compared with doses given by Weitz and Thomas (1985) in parentheses as follows: May – 1.20 (1.64) rem; June – 0.27 (0.56) rem; July – 0.17 (0.33) rem; August – 0.08 (0.18) rem. At Bikini Atoll, the same comparisons are as follows: May – 0.63 (0.18) rem; June – 0.20 (0.04) rem; July – 0.23 (0.37) rem; August – 0.06 (0.10) rem. Thus, at Bikini Atoll, reconstructed doses given by Weitz (1995a) are higher during the first two months but are lower during the last two months. Reasons for the differences in reconstructed doses were not discussed by Weitz (1995a), who noted only that all documented instances of fallout on residence islands at the two atolls were taken into account.

95% of all badge readings in the other 15 cases that have lower mean badge readings; the number of readings in those cases ranges from three to 55.

Weitz (1995a) compared reconstructed mean doses with film badge readings for participants in an Army administrative detachment that was stationed on Enewetak Island. These comparisons for a number of common badging periods for participants in this unit are given in Table 14.1. During the first six periods, the reconstructed mean dose is comparable to or greater than the mean badge reading, and use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that far exceeds the estimated upper bound ($95^{th}$ percentile) of the distribution of badge readings without accounting for the bias factor of 1.5 in badge readings. During the last two periods, the reconstructed mean dose is substantially less than the mean badge reading, but use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds at least 95% of all badge readings when the bias in badge readings is taken into account. Weitz (1995a) also noted that the average sum of badge readings for the entire period through August 4 of 1.88 rem does not differ greatly from the reconstructed mean dose during the entire period of 1.65 rem.

**Table 14.1.** Comparison of film badge readings for participants in Army administrative detachment on Enewetak Island with reconstructed mean doses[a]

| Start date | End date | Number of badges | Mean badge reading (upper bound) (rem)[b] | Reconstructed dose (rem) |
|---|---|---|---|---|
| April 4 | June 7 | 20 | 1.29 (1.61) | 1.29 |
| April 12 | May 31 | 34 | 0.65 (0.81) | 1.20 |
| April 12 | June 5 | 12 | 0.86 (1.18) | 1.27 |
| April 12 | June 17 | 16 | 1.31 (1.57) | 1.39 |
| April 12 | June 27 | 50 | 1.20 (1.56) | 1.45 |
| April 12 | June 28 | 50 | 1.33 (1.67) | 1.46 |
| June 27 | August 4 | 50 | 0.59 (0.69) | 0.20 |
| June 28 | August 4 | 50 | 0.65 (0.86) | 0.19 |

[a] See Table 2 of Weitz (1995a).

[b] Upper bound of distribution of film badge readings is intended to be $95^{th}$ percentile and is calculated on the basis of standard deviation given by Weitz (1995a) multiplied by 1.645.

Weitz (1995a) compared reconstructed mean doses with film badge readings for participants in a Navy boat pool that was stationed on Eneu Island at Bikini Atoll. These comparisons for a number of common badging periods for participants in this unit are given in Table 14.2. In all cases, the reconstructed mean dose is comparable to or greater than the mean badge reading, and use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that far exceeds the estimated upper bound (95$^{th}$ percentile) of the distribution of badge readings without accounting for the bias in badge readings.

**Table 14.2.** Comparison of film badge readings for participants in Navy boat pool on Eneu Island at Bikini Atoll with reconstructed mean doses[a]

| Start date | End date | Number of badges | Mean badge reading (upper bound) (rem)[b] | Reconstructed dose (rem) |
|---|---|---|---|---|
| April | June 6 | 65 | 0.18 (0.26) | 0.69 |
| June 6 | July 7 | 15 | 0.16 (0.23) | 0.29 |
| June 6 | July 25 | 35 | 0.33 (0.45) | 0.36 |
| June 6 | July 31/August 1 | 11 | 0.41 (0.52) | 0.38 |

[a] See Table 4 of Weitz (1995a).

[b] Upper bound of distribution of film badge readings is intended to be 95$^{th}$ percentile and is calculated on the basis of standard deviation given by Weitz (1995a) multiplied by 1.645.

Weitz (1995a) also noted that film badge readings for participants in unidentified units on Japtan Island at Enewetak Atoll are about 60% higher than badge readings on Enewetak or Parry Island during comparable exposure periods. On the basis of this comparison, reconstructed mean doses on Japtan Island were assumed to be 60% higher than tabulated doses on Enewetak Atoll.

NuTRIS was accessed to investigate whether there are additional film badge readings that could be compared with reconstructed mean doses on residence islands. However, we could not distinguish between badge readings for units that were included in comparisons given by Weitz and Thomas (1985) and Weitz (1995a) discussed above and units that were not included, and we could not always determine whether a given unit participated in special activities that were not taken into account in dose reconstructions. Thus, we have assumed that comparisons in the SAIC memoranda are reasonably representative of all comparisons that could be made.

### 14.3.2 *Exposures on Ships*

Information in SAIC memoranda that can be used to compare reconstructed doses on ships with film badge readings is summarized as follows:

- McRaney (1992b) gives a reconstructed dose on the USS DE HAVEN during the period May 12 – August 5 of 0.36 rem. The single film badge reading reported by McRaney (1992b) that applies to this time period is 0.62 rem.[45]
- McRaney (1993a) gives a reconstructed dose on the USS BOXER during the period from the beginning of the operation through June 30 of about 0.67 rem. The mean film badge reading for 980 participants during that period is 0.735 rem, and the 95th percentile of the distribution of badge readings given by Weitz (1995b) is 1.1 rem. Use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds more than 95% of all badge readings without accounting for the bias in badge readings.
- Weitz (1995c) gives a reconstructed dose on the USS REHOBETH during the period April 19 – May 28 of 0.32 rem. The mean film badge reading for about 160 participants during that period is 0.27 rem, and the 95th percentile of the distribution of badge readings that we calculated from the reported standard deviation is 0.47 rem. Only one badge reading exceeds the reconstructed mean dose by more than a factor of three. When the bias factor of 1.5 in badge readings is taken into account, no badge readings exceed the reconstructed mean dose by more than a factor of three.
- Weitz (1995e) gives a reconstructed dose on the USS MOCTOBI during the period April 9 – June 16 of 0.74 rem. The mean film badge reading for 38 participants during that period is 0.73 rem, and the 95th percentile of the distribution of badge readings that we calculated from the reported standard deviation is 1.01 rem. For a smaller group of 15 participants, the mean badge reading (95th percentile) during that period is 0.64 (0.82) rem, and a second set of readings during the period June 15–16 is 0.54 (0.80) rem;

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[45] During the period beginning on or before May 12 and ending on August 5–12, NuTRIS gives 213 film badge readings that range from 0.22 to 1.76 rem. Fewer than 5% of those badge readings exceed the reconstructed mean dose by more than a factor of three when the bias factor of 1.5 in badge readings is taken into account. We have no information to indicate why the many badge readings in NuTRIS were not reported by McRaney (1992b).

we presume that the latter readings represent exposures during special activities that were not experienced by most crew members and were not taken into account in the dose reconstruction. The distribution of badge readings in the first group given by Weitz (1995e) indicates that no badge readings exceed the reconstructed mean dose for an average crew member by as much as a factor of three without accounting for the bias in badge readings.

- Weitz (1995g) gives a reconstructed dose on the USS HOOPER ISLAND during the period April 20 – June 23 of 0.50 rem. The mean film badge reading for about 350 participants during that period is 0.47 rem, and the 95$^{th}$ percentile of the distribution of badge readings that we calculated from the reported standard deviation is 0.80 rem. Only one film badge reading exceeds the reconstructed mean dose by more than a factor of three. When the bias factor of 1.5 in badge readings is taken into account, no badge readings exceed the reconstructed mean dose by more than a factor of three.
- Weitz and McRaney (1995) gives a reconstructed dose on the USS LANSING during the period May 21 – June 13 of essentially zero on the basis of reports that this ship received no fallout while stationed at Enewetak Atoll. All personnel on this ship apparently were issued film badges during this time period. A majority (54%) of all film badges recorded a dose of zero. The remaining badge readings range from 50 to 146 mrem, with an average of 76 mrem. Weitz and McRaney (1995) concluded that the non-zero badge readings probably resulted from exposure to residual contamination during shore liberty on residence islands at Enewetak Atoll that received fallout from two shots at this operation prior to the ship's arrival at Enewetak. During later operations at Johnston Island during the periods July 15 – August 1 and August 7–12, Weitz and McRaney (1995) estimated an upper bound dose of about 0.4 rem for crew members who were involved in recovery, temporary storage, and transfer of an instrumented pod that was attached to a missile used in a high-altitude test; the estimated upper bound was based on measured exposure rates near an instrument pod. However, no records of film badges that were issued to crew members during these time periods were located.

In the first five cases summarized above, reconstructed doses were based on measured exposure rates on the ship. In the four cases where a reconstructed dose was compared with a substantial

number of film badge readings, use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that exceeds at least 95% of all badge readings regardless of whether the bias factor of 1.5 in badge readings is taken into account. In the last case, it is likely that doses from exposure on the ship during the period May 21 – June 13 were essentially zero, in agreement with the reconstructed dose, even though a substantial number of film badge readings are above a nominal minimum detectable dose of 50 mrem (see Section 1.4). Given that all crew members apparently were badged during the period when the reconstructed dose on the ship applies, a possible discrepancy between the reconstructed dose and film badge readings above 50 mrem should not be significant.[46] The reconstructed dose in all cases is less than 1 rem.

Many other SAIC memoranda discuss assumptions that were used in dose reconstructions on ships and present distributions of film badge readings for crew members. However, information in those memoranda does not allow a comparison of reconstructed doses with badge readings. In some cases, reconstructed doses were based in part on assumptions about exposure rates that were adjusted to achieve agreement between the reconstructed dose and mean film badge reading or similar assumptions on a nearby ship (Weitz, 1995d,h–k,m,n,p; 1996a–d; 1997c; 1998; 1999a). In other cases, assumptions about exposure rates that were developed on the basis of available data and used to reconstruct doses during a period covered by film badge readings are described, but the reconstructed dose during that period was not reported (Weitz, 1995f,s,t; 1996e–g; 1997b; 1999b). In all these cases, the mean film badge reading was used in lieu of a reconstructed dose during the covered period, and reconstruction doses were used only to estimate doses during later periods that were not covered by badge readings. The approaches in all these cases are understandable when nearly all crew members had badge readings during times spent in a test area and a reconstructed dose during those times is not needed. However, when unadjusted reconstructed doses during periods covered by film badges were not reported, the adequacy of a 3X upper bound factor cannot be evaluated. It could be informative, for example, to compare unadjusted reconstructed doses with film badge readings in cases where mean badge readings are greater than 1 rem (Weitz, 1995j,t; 1996e,f).

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[46] Weitz and McRaney (1995) recommended that all assigned doses to crew members on the USS LANSING during the period May 21 – June 13 should be based on film badge readings, rather than the reconstructed dose.

## 14.4 Summary of Analysis

There are no published dose reconstructions for military units at Operation HARDTACK I. However, information in several SAIC memoranda can be used to compare reconstructed doses on residence islands or ships with film badge readings.

Many comparisons of reconstructed doses on residence islands at Enewetak and Bikini Atolls with film badge readings indicate that there is good agreement between the two, and that use of a 3X upper bound factor on a reconstructed mean dose gives an upper bound that exceeds at least 95% of all badge readings when the bias factor of 1.5 in badge readings at this operation is taken into account. These cases provide comparisons that cover most of the time period of exposures on residence islands during this operation.

In all cases where reconstructed doses on ships can be compared with a substantial number of film badge readings, use of a 3X upper bound factor on the reconstructed dose gives an upper bound that exceeds at least 95% of all badge readings. However, given that only a few comparisons could be made on ships, we believe that it would be informative to compare reconstructed doses with film badge readings in several additional cases where reconstructed doses were not reported in SAIC memoranda if information on reconstructed doses is available, especially when the mean badge reading is greater than 1 rem.

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# 15. OPERATIONS AT PPG – IX.
# OPERATION DOMINIC I (1962)

## 15.1 Unit Dose Reconstructions

Operation DOMINIC I consisted of 35 tests that were conducted near Christmas or Johnstone Island, including 29 airdrop airburst shots, five high-altitude rocket shots, and a Polaris-launched airburst shot, and one underwater test that was conducted at a location about 370 miles southwest of San Diego, California (Berkhouse et al., 1983). Except at the underwater test, there was little or no fallout or residual radioactive material near surface ground zero.

There are no published dose reconstructions for military units at Operation DOMINIC I, and only two dose reconstructions for specific units are given in SAIC memoranda. Those dose reconstructions are discussed in Section 15.3.

## 15.2 Discussion of Film Badge Dosimetry

Film badges were issued to all participants who were stationed on Christmas and Johnstone Islands or on ships that were involved in tests. However, many badges were not sealed properly and were found to be damaged due to effects of moisture, light, and heat (Berkhouse et al., 1983; NRC, 1989). Many badges indicated exposures above 0.4 rem even when there was little or no possibility of exposure and readings should have been zero. The NRC (1989) report concluded that unless a participant was involved in certain activities, any indicated film badge exposure was likely to have been caused by environmental damage. Activities that could have involved exposure are described in the following section.

## 15.3 SAIC Memoranda

Several memoranda that addressed exposures during Operation DOMINIC I were prepared by SAIC (Goetz, 1998; McRaney, 1992, 1994a,b; Edwards, 1995; Stiver, 2002). Some of those memoranda addressed the general concern that most non-zero film badge readings were caused by environmental damage, rather than exposure to radiation (Goetz, 1998; McRaney,

1992, 1994a,b). In the other memoranda, a dose of zero was assigned to particular units on the basis of the consideration that there was no potential for exposure (Edwards, 1995; Stiver, 2002).

The NTPR Program's current policy on assigning doses to participants with film badge readings is given in the *Standard Operating Procedures Manual* (DTRA, 2008; Appendix B-10); see also McRaney (1994a,b). To account for the problem of environmental damage to many film badges, as well as knowledge of exposure environments, a dose of zero is assigned, regardless of a badge reading, unless a participant was a member of one of the following groups:

- Cloud sampling aircrews or ground crews that worked on contaminated aircraft;
- Crew members of the USS SIOUX, which was involved in sampling a radioactive pool of water following the underwater test;
- Personnel that were involved in recovery or handling of radioactive instrumented pods, rocket nose cones, or other activated or contaminated material (e.g., target rafts) at several tests;
- Radiation-safety monitors;
- Personnel that were involved in recovery or decontamination operations after any missile incident that resulted in plutonium contamination of any portion of Johnstone Island, or deposition of plutonium-contaminated debris on that island or on any ship that operated in the vicinity.

This policy is in accordance with a previous recommendation (NRC, 1989). SAIC memoranda do not give reconstructed doses for any of these groups.

In the two cases where a reconstructed mean dose of zero is given in SAIC memoranda (Edwards, 1995; Stiver, 2002), film badge readings were not reported, nor are any badge readings given in NuTRIS. Even if badge readings were available, however, non-zero readings above a nominal minimum detectable dose of 50 mrem (see Section 1.4) would be considered unreliable and should not be compared with a reconstructed dose (McRaney, 1994a).

### 15.4 Summary

Although all participants at Operation DOMINIC I were issued film badges, there are no opportunities to compare reconstructed doses with film badge readings. Doses to most

participants probably were essentially zero, and many film badges experienced environmental damage that compromised their readings. In addition, reconstructed doses have not been reported for units that could have received substantial exposures.

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# 16. SUMMARY AND CONCLUSIONS

This section presents a summary of comparisons of reconstructed doses from external exposure to gamma rays with film badge readings for military participants at atmospheric nuclear weapons tests, as presented in Sections 2–15. The purpose of these comparisons is to evaluate the adequacy of a generic 3X upper bound factor that has been applied to reconstructed mean doses or point estimates of dose with no uncertainty to obtain upper bounds since 2003. The adequacy of a 3X upper bound factor is evaluated on the basis of comparisons of reconstructed doses with film badge readings reported in published unit dose reconstructions or SAIC memoranda. Additional film badge readings given in NuTRIS are discussed but were not used in this analysis (see Section 1.5).

We evaluated the adequacy of a 3X upper bound factor on the basis of comparisons of reconstructed doses for specific military units at a particular test or tests at a particular operation with distributions of film badge readings for participants in those units. Use of a 3X upper bound factor is considered to be adequate in a specific case if the resulting upper bound of a reconstructed dose exceeds at least 95% of all film badge readings. Performing evaluations on a unit-by-unit basis conforms to the way dose reconstructions are presented and compared with film badge readings in published reports and SAIC memoranda, and it facilitates an identification of the kinds of exposure scenarios in which use of a 3X upper bound factor may not be adequate. No attempt has been made to evaluate the adequacy of a 3X upper bound factor on the basis of aggregations of comparisons of reconstructed doses with film badge readings in two or more cases, even when different cases involved units that were exposed under similar conditions.

In evaluating the adequacy of a 3X upper bound factor, we have assumed that the relationship between a reading of a film badge that was worn by a participant in roentgen (R) and the corresponding dose to the whole body in rem, which is the quantity calculated in dose reconstructions, should be taken into account. This assumption is based on the view that upper bounds of reconstructed external gamma doses should be at least upper 95% confidence limits of true doses, rather than upper 95% confidence limits of doses that are estimated by assuming that a badge reading in R gives a whole-body dose in rem, as is assumed in dose assessments in the NTPR Program. Badge readings in R generally overestimate whole-body doses in rem, and the bias in badge readings can be significant. In several comparisons, we found that an upper bound

factor somewhat greater than three would be required to give upper bounds of reconstructed doses that exceed at least 95% of all film badge readings if the bias in badge readings is ignored, but that a 3X upper bound factor is adequate if the bias in badge readings is taken into account. Bias factors for film badges at the various operations range from 1.1 to 2.1 (see Table 1.1).

In comparing reconstructed doses for a given unit with film badge readings, a judgment must be made about the minimum number of badge readings that would allow a meaningful comparison. This issue arises in several cases of exposure to residual gamma radiation where only a few badge readings were reported in published unit dose reconstructions or SAIC memoranda. In this analysis, we have assumed that comparisons are meaningful only in cases where at least five relevant badge readings were reported. This assumption is somewhat arbitrary, but we believe that meaningful comparisons with reconstructed doses probably can be made on the basis of as few as five badge readings. For example, five badge readings could give a reasonable indication of the distribution of doses and could allow an identification of an outlier.

Given that use of a 3X upper bound factor should give upper bounds of reconstructed doses that exceed at least 95% of all relevant film badge readings, judgment also is required in evaluating the adequacy of a 3X upper bound factor when there are fewer than 20 badge readings. In such cases, we judged that a 3X upper bound factor is adequate if no more than one badge reading exceeds the reconstructed mean dose by more than a factor of three.

External gamma doses that were received by participants varied widely, from essentially zero to several rem. In this report, we categorized doses above 1 rem as relatively high and doses below 1 rem as relatively low. Although this categorization is somewhat arbitrary, it allows an identification of cases of greater importance with respect to adjudicating claims for compensation for cancer or other radiogenic diseases on the basis of estimates of dose. This categorization also allows an evaluation of whether inadequacies in use of a 3X upper bound factor are more frequent at relatively low doses than at higher doses.

In the following two sections, summaries of comparisons of reconstructed external gamma doses with film badge readings are presented for operations at NTS and PPG separately. This separation is based on a consideration that conditions of exposure and challenges in reconstructing doses often were significantly different at the two test sites. A concluding section summarizes the nature of exposure situations in which use of a 3X upper bound factor was found to be inadequate and discusses how those inadequacies might be addressed. It is important to

emphasize that judgments about the adequacy of a 3X upper bound factor are subjective in some cases, in that they depend on how the available information on reconstructed doses and film badge readings is interpreted and those interpretations are not always unambiguous.

## 16.1 Summary of Evaluations at NTS

At NTS, nearly all comparisons of reconstructed doses with film badge readings involved forward observers at locations close to ground zero at the time of a detonation, observers or maneuver troops at locations close to ground zero at times shortly after a detonation, or members of other units that engaged in a variety of activities on the ground in forward areas at times before or after a detonation (e.g., damage evaluators, engineering support units, signal units). A few comparisons involved aircrews and helicopter crews, but there are no comparisons for cloud samplers or ground crews that handled cloud samples or were exposed to contaminated aircraft.

An important characteristic of exposures at NTS is that they generally were episodic. For example, exposures of observers, maneuver troops, and other ground units occurred mainly during short periods of time spent in forward areas on the test site, and doses during times spent at off-site locations were insignificant. Thus, exposures often occurred at about the same time that field survey data were obtained at or near locations of exposure, and a need to extrapolate measured exposure rates over long periods of time did not arise. Another important characteristic is that exposure rates due to fallout or neutron activation products in surface soil at NTS usually did not vary greatly over small distances or spatial variations usually were sufficiently well understood on the basis of measurements and calculations.

The following sections summarize the results of our analysis of cases involving exposure to initial or residual gamma radiation at NTS.

### 16.1.1 *Exposures to Initial Gamma Radiation*

The results of our analysis of exposures to initial gamma radiation at NTS on the basis of reconstructed doses and film badge readings given in published unit dose reconstructions or SAIC memoranda are summarized as follows:

- In all cases where reconstructed initial gamma doses to forward observers were compared with film badge readings, including readings of badges that were placed at various locations but were not worn by participants as well as badges that were worn by those observers, use of a 3X upper bound factor on a reconstructed mean dose gives an upper bound that exceeds all badge readings.

Use of a 3X upper bound factor was found to be more than adequate at 18 shots in four operations (all operations considered in this analysis except TUMBLER-SNAPPER), and at varying distances from ground zero. This is a significant result when doses to some forward observers exceeded 10 rem.

**16.1.2** *Exposures to Residual Gamma Radiation*

The results of our analysis of exposures to residual gamma radiation at NTS on the basis of reconstructed doses and film badge readings given in published unit dose reconstructions or SAIC memoranda are summarized in Table 16.1 and as follows:

- In 38 cases of exposure to residual gamma radiation, reconstructed doses were compared with readings of at least five film badges. In 34 cases, including 11 cases where the reconstructed mean dose and most badge readings are above 1 rem, use of a 3X upper bound factor on a reconstructed mean or high-sided dose gives an upper bound that exceeds at least 95% of all badge readings. In three of the four cases where use of a 3X upper bound factor does not appear to be adequate, reconstructed doses and most badge readings are at or below a nominal minimum detectable dose of 50 mrem, and we do not believe that discrepancies between reconstructed doses and badge readings are significant in such cases. The one remaining case where use of a 3X upper bound factor is not adequate, which is discussed below, involved exposure of a small group of participants in Task Force WARRIOR (Project 50.1) at Operation PLUMBBOB, Shot SMOKY; most badge readings in that group are above 1 rem.

**Table 16.1.** Summary of comparisons of reconstructed doses from exposure to residual gamma radiation with film badge readings at NTS[a]

| | Doses < 1 rem | | Doses > 1 rem | |
|---|---|---|---|---|
| Operation | Yes | No | Yes | No |
| BUSTER-JANGLE | 8 | 2[b] | 1[c] | |
| TUMBLER-SNAPPER | 3 | | | |
| UPSHOT-KNOTHOLE | | | 6 | |
| TEAPOT | 3[d] | | | |
| PLUMBBOB | 9 | 1[b] | 4 | 1 |

[a] Comparisons are based on readings of at least five film badges that were reported in published unit dose reconstructions or SAIC memoranda. "Yes" means that use of 3X upper bound factor on reconstructed mean or high-sided dose gives upper bound that exceeds at least 95% of all badge readings; "No" means that use of 3X upper bound factor gives reconstructed upper bound that does not exceed at least 95% of all badge readings.

[b] Reconstructed mean or high-sided dose and many film badge readings are below nominal minimum detectable dose of 50 mrem. Comparisons in these cases are not considered meaningful.

[c] Not included is a case involving exposure of an engineering support unit following Shot UNCLE where reconstructed mean dose is 1.4 rem but all film badge readings are less than 0.3 rem. It is likely that all badge readings apply to participants who were exposed at locations different from locations of exposure assumed in the dose reconstruction, and a comparison of the reconstructed dose with badge readings probably is not meaningful (see Section 2.2).

[d] In three additional cases involving exposure of observers, a substantial number of film badge readings are given in NuTRIS, and use of a 3X upper bound factor is adequate when reconstructed doses are compared with those badge readings in all cases. However, the significance of these comparisons is difficult to evaluate when published report on unit dose reconstructions indicated that film badge records were inadequate in those cases and no badge readings were reported (see Section 5.1.2.2).

In the case involving Task Force WARRIOR, use of a 3X upper bound factor on the reconstructed mean doses, which depend on a participant's activities, gives upper bounds that exceed at least 95% of the film badge readings for all members of the task force. However, all badge readings in a small group of less than 5% of the members are about an order of magnitude higher than reconstructed mean doses and are a factor of about 2–5 higher than all other badge readings in the task force. To give an upper bound of a reconstructed dose that exceeds at least 95% of all badge readings in the small group, an upper bound factor of about 5–12 is required, depending on a participant's activities. A plausible explanation of this large discrepancy is that the radiation environment in which this group was exposed at Shot SMOKY was characterized incorrectly, due to a lack of field survey data in the area where higher exposures occurred and the

unexpected presence of fallout from Shot SMOKY during the group's maneuver in that area (see Section 6.1.2.1). However, the large discrepancy between reconstructed doses and film badge readings in the small group in Task Force WARRIOR apparently does not have potentially important consequences in regard to estimating doses to members of that group. Information in NuTRIS indicates that all doses that have been assigned to those participants are based on film badge readings, and that none of those participants has been assigned a much lower reconstructed mean dose or upper bound.

Three cases where use of a 3X upper bound factor was judged to be adequate are discussed further below.

In a case involving observers at Operation BUSTER-JANGLE, Shot DOG (see Section 2.1.2.2), the high-sided reconstructed dose and more than 95% of all film badge readings are below a nominal minimum detectable dose, but a small fraction of badge readings exceed the reconstructed dose by more than a factor of ten. The unusually high badge readings were attributed to unauthorized and documented excursions of a few participants who proceeded closer to ground zero than most observers. Regardless of the cause of the high badge readings, this discrepancy does not have important consequences when all observers at this shot apparently have a badge reading and there should be no need to assign a reconstructed dose to any observer.

In a case involving observers at Operation TUMBLER-SNAPPER, Shot FOX (see Section 3.1.2), information in NuTRIS indicates that the reconstructed mean dose has been assigned to unbadged observers in spite of evidence that the reconstructed dose is too low. We believe that the mean of all film badge readings should be assigned to unbadged observers.

In a case involving observers and maneuver troops at Operation TUMBLER-SNAPPER, Shot GEORGE (see Section 3.1.2), a judgment that use of a 3X upper bound factor is adequate depends somewhat on an assumption that all film badge readings apply to maneuver troops, who apparently received higher doses than observers. However, when the large bias in badge readings at that operation is taken into account, an upper bound factor of only slightly greater than three is required even if some of the highest badge readings apply to observers. Furthermore, all badge readings are low (0.3 rem or less). We do not believe that a possible inadequacy of a 3X upper bound factor in this case is significant.

Four additional cases that were not included in our analysis are mentioned in Table 16.1. One case at Operation BUSTER-JANGLE, where the reconstructed dose was above 1 rem, was

excluded on the basis of an argument by SAIC analysts that available film badge readings apply to exposures that were not taken into account in the dose reconstruction. In three cases at Operation TEAPOT, a substantial number of film badge readings are given in NuTRIS but no readings were reported in the published unit dose reconstruction, which stated that film badge data were inadequate to provide meaningful comparisons with reconstructed doses. However, there was no apparent reason why the badge readings in NuTRIS were considered inadequate. Given that the adequacy of a 3X upper bound factor could be evaluated in very few cases at Operation TEAPOT, we believe that useful information might be obtained from a further investigation of whether film badge readings in NuTRIS are relevant in those three cases.

Overall, the analyses at NTS indicate that use of a 3X upper bound factor on a reconstructed mean or high-sided dose gives an upper bound that exceeds at least 95% of all film badge readings in nearly all cases where meaningful comparisons could be made. In the one case where there is a large and meaningful discrepancy of about an order of magnitude between reconstructed mean doses and film badge readings, we do not believe that the discrepancy indicates an important problem with methods of dose reconstruction at NTS. Rather, the most plausible explanation in that case is that the discrepancy is due mainly to an inadequate characterization of the radiation environment in which unexpectedly high exposures occurred. That case represents a situation, which occurred rarely at NTS, where exposure rates were not measured near locations of exposure at times shortly after a detonation and, thus, the dose reconstruction had to be based on an extrapolation of measured exposure rates at distant locations and in other directions from ground zero.

Comparisons of reconstructed doses with film badge readings are lacking for participants in some units at NTS that could have received relatively high doses. For example, there are no reconstructed doses for cloud samplers or ground crews that handled cloud samples or contaminated aircraft. However, this could be an important concern only if participants in those units do not have badge readings during periods of exposure. We did not investigate whether film badge readings for those participants are available.

In addition, there are no film badge readings for about 1,000 participants in Task Force RAZOR at Operation TEAPOT (see Section 5.1.2). This could be an important concern when reconstructed mean doses to various units in that task force range from 0.5 to 1.8 rem. However, since use of a 3X upper bound factor was found to be adequate in several cases involving

maneuver units at Operations UPSHOT-KNOTHOLE and PLUMBBOB where doses were above 1 rem, we have no reason to believe that use of a 3X upper bound factor would be inadequate in obtaining upper bounds of reconstructed doses to members of that task force.

### 16.2 Summary of Evaluations at PPG

At PPG, nearly all comparisons of reconstructed doses with film badge readings involved crew members on ships or participants stationed on residence islands. With one exception, dose reconstructions have not been performed at PPG for cloud samplers, other aircrews, or ground crews that handled cloud samples or were exposed to contaminated aircraft. Furthermore, there are few comparisons of reconstructed doses with film badge readings in cases of exposure on contaminated non-residence islands and a general absence of comparisons in other situations where mission badges were issued to participants who entered contaminated areas for short time periods and for specific purposes (e.g., to retrieve equipment following a test).

Exposures at PPG often differed from exposures at NTS in important ways. Many exposures to fallout on ships or residence islands or to contamination on a ship's hull were protracted over periods of days or weeks. Thus, dose reconstructions often had to be based on extrapolations of measured exposure rates over long periods of time. Furthermore, exposure rates on a ship or an island during or after a fallout episode were not always reported, and exposure rates in those cases had to be estimated on the basis of measurements on nearby ships or islands. Although fallout depositions at locations of exposure on residence islands probably were nearly uniform in most cases, given the considerable distances of those islands from locations of detonations, and concentrations of fallout in air presumably were uniform over the area of a ship, fallout depositions on ship surfaces probably were highly non-uniform in many cases, due to the effects of a ship's superstructure on wind flow at the air-ship interface. Finally, exposure of participants on ships or islands to initial gamma radiation did not occur at PPG.

In this analysis, reconstructed doses and comparisons with film badge readings were considered at nine operations at PPG. However, comparisons at Operations SANDSTONE, WIGWAM, and DOMINIC I are not reiterated in this summary. Levels of fallout on ships and islands at Operation SANDSTONE were low, and since all reconstructed doses and nearly all badge readings are below a nominal minimum detectable dose of 50 mrem in cases where

comparisons could be made, comparisons are not meaningful. At Operations WIGWAM and DOMINIC I, doses to most participants were low (below about 0.1 rem), and information on dose reconstructions and film badge readings did not permit comparisons to be made.

In the following sections, comparisons of reconstructed doses with film badge readings are summarized for units on ships and other units separately. Exposure environments generally were more complex and uncertain on ships than on islands, and challenges in reconstructing doses were greater on ships.

### **16.2.1** *Exposures on Ships*

The results of our analysis of exposures to residual gamma radiation on ships at PPG on the basis of reconstructed doses and film badge readings given in published unit dose reconstructions or SAIC memoranda are summarized in Table 16.2 and as follows:

- In 93 cases of exposure to residual gamma radiation on ships, reconstructed doses were compared with readings of at least five film badges.[47] In 73 cases, including all five cases where most film badge readings are above 1 rem, use of a 3X upper bound factor on a reconstructed mean dose gives an upper bound that exceeds at least 95% of all film badge readings. In 15 cases, use of a 3X upper bound factor is not adequate. The remaining five cases were excluded on the grounds that the reconstructed mean dose and readings of all film badges or all badges but one are below a nominal minimum detectable dose of 50 mrem and comparisons in those cases are not meaningful.

Discussions in the following sections consider judgments that were involved in evaluating some of the comparisons on ships, the 15 cases where use of a 3X upper bound factor was judged to be inadequate, and the five cases that were excluded from the analysis.

[47] At PPG, a single case is defined by exposure on a single day or succession of days, as determined by periods covered by reconstructed doses and film badge readings, without regard for whether multiple cases on the same ship or residence island involved the same individuals.

**Table 16.2.** Summary of comparisons of reconstructed doses from exposure to residual gamma radiation with film badge readings at PPG – I. Comparisons on ships[a]

| | Doses < 1 rem | | Doses > 1 rem | |
|---|---|---|---|---|
| Operation | Yes | No | Yes | No |
| CROSSROADS | 13[b] | 1(?) | | |
| GREENHOUSE[c] | 11 | 4 | | |
| IVY[d] | 10 | 4 | | |
| CASTLE | 24[e] | 5[f] | 5 | |
| REDWING | 5[g] | 1 | | |
| HARDTACK I | 5[h] | | | |

[a] Comparisons are based on readings of at least five film badges that were reported in published unit dose reconstructions or SAIC memoranda. "Yes" means that use of 3X upper bound factor on reconstructed mean dose gives upper bound that exceeds at least 95% of all badge readings; "No" means that use of 3X upper bound factor gives reconstructed upper bound that does not exceed at least 95% of all badge readings.

[b] In two cases of exposure at Shot ABLE, reconstructed mean doses and all film badge readings are below nominal minimum detectable dose of 50 mrem.

[c] Five cases of exposure at Shot GEORGE where reconstructed mean dose and readings of all film badges or all badges but one are below nominal minimum detectable dose of 50 mrem are not included (see text).

[d] Reconstructed mean doses on all ships where film badge readings were available are below nominal minimum detectable dose of 50 mrem; in ten cases, substantial numbers of badge readings are above nominal minimum detectable dose.

[e] Included in this total are three cases where there were fewer than 20 film badge readings and only one badge reading exceeds reconstructed mean dose by more than a factor of three (see text).

[f] In one case, upper bound factor required to give reconstructed upper bound dose that exceeds at least 95% of all film badge readings is only slightly greater than 3 and there were only 11 badge readings. Possible inadequacy of a 3X upper bound factor in this case probably is not significant.

[g] In one case, reconstructed mean dose could not be compared with film badge readings on the basis of information available to us. However, on the basis of "threshold dose" calculated by SAIC analyst from upper bound of reconstructed dose and uncertainties in badge readings, highest reliable badge reading probably does not exceed reconstructed mean dose by more than a factor of three (see Section 13.3).

[h] In one case, reconstructed dose is essentially zero based on absence of fallout on a ship, and majority of film badges recorded zero dose. Agreement of reconstructed dose with film badge readings is based on assumption that substantial number of badge readings above 50 mrem represent exposures during shore liberty, rather than on the ship. Possible discrepancy between reconstructed dose and film badge readings is not significant when all crew members on the ship were badged (see Section 14.3.2).

**16.2.1.1** *Operation CROSSROADS*. The one case at Operation CROSSROADS where use of a 3X upper bound factor appears to be inadequate involved a single day's exposure of a boarding party that was billeted on the support ship USS RECLAIMER (see Section 7.1 and Table 7.1). All six badge readings are well above the reconstructed dose, and the highest badge readings exceeds the reconstructed dose by a factor of about 6 when the bias in badge readings is taken into account. The high badge readings were attributed to exposures during additional reported boardings that could not be reconciled with records of the ship's activities on that date and were not taken into account in the dose reconstruction. Given the uncertainty in the activities of badged participants, this comparison is marked as questionable in Table 16.2.

In four cases involving boarding parties on the target ship USS INDEPENDENCE, we assumed that reconstructed doses should be reduced by a factor of 0.34 to account for the likelihood that members of boarding parties spent most of the time below the weather deck (see Section 7.1 and Table 7.2). With that reduction, use of a 3X upper bound factor is still adequate in all four cases when the bias in film badge readings is taken into account.

We caution that comparisons of reconstructed doses with film badge readings at this operation may not be definitive when comparisons could be made in relatively few cases, most film badges were turned in within one day of their issuance, and there was little potential for high doses on most days and in most exposure situations (see Section 7.3).

**16.2.1.2** *Operation GREENHOUSE*. In comparing reconstructed doses with film badge readings on ships at Operation GREENHOUSE, we accepted an argument by SAIC analysts that the tendency for reconstructed doses to systematically underestimate badge readings can be explained, at least in part, by the duties of virtually all badged participants, which resulted in exposures substantially higher than exposures of average crew members that were the focus of dose reconstructions (see Section 9.1.1.1.1). In the four cases where use of a 3X upper bound factor is inadequate when reconstructed doses are increased to account for the presumably higher exposures of badged participants (the USS CURTISS at Shot EASY and the USS CABILDO, USNS MOWER, and USS SPROSTON at Shot ITEM), the highest film badge readings range from 0.18 to 2.4 rem, and the required upper bound factor is about 4–5 in three cases and about 40 on the USS SPROSTON at Shot ITEM. In two of those cases, exposure rates were not measured on the ship but were assumed to be determined by measurements on a nearby ship or

island. If reconstructed doses were not increased to account for the presumably higher exposures of badged participants, use of a 3X upper bound factor would be inadequate in two additional cases. The required upper bound factor would be about 4 in one case and 7 in the other. The required upper bound factor also would increase in the four cases summarized above.

On the USS SPROSTON at Shot ITEM, the large discrepancy between the reconstructed mean dose, which is about 0.003 rem when the presumably higher exposures of badged participants are taken into account, and readings of all eight film badges of 0.08–0.18 rem seems inexplicable when the dose reconstruction was based on reported exposure rates on that ship. SAIC analysts did not offer an explanation of the large discrepancy.

In two cases at Shot GEORGE where reconstructed doses are 10 mrem or less, a single badge reading exceeds a nominal minimum detectable dose of 50 mrem and is much higher than the reconstructed mean dose; there is a total of seven badge readings in one case and 17 in the other (see Section 9.1.1.1.1). Given the absence of fallout on ships at Shot GEORGE and the preponderance of badge readings of zero, we presume that the two high badge readings are anomalous and do not represent exposures of other unbadged crew members. Since the reconstructed doses and most badge readings are less than a nominal minimum detectable dose, these cases, as well as the other three cases at Shot GEORGE where all badge readings are zero, are not included in the comparisons summarized in Table 16.2.

**16.2.1.3** *Operation IVY*. Doses at Operation IVY generally were low, and we accepted arguments by SAIC analysts that unusually high film badge readings on the USS RENDOVA, OAK HILL, and ESTES apply to participants who were involved in activities apart from most crew members that were not taken into account in dose reconstructions (see Section 10.1). In those cases, most badge readings are less than a nominal minimum detectable dose of 50 mrem or exceed the reconstructed mean dose by less than a factor of three. However, in four cases on the USS CARPENTER, O'BANNON, FLETCHER, and YUMA where most badge readings exceed the reconstructed mean dose by more than a factor of three and are above a nominal minimum detectable dose of 50 mrem, we did not accept arguments that badge readings should be discounted; the highest badge readings in those cases range from 0.12 to 0.22 rem.

On the USS CARPENTER, O'BANNON, and FLETCHER, it is plausible, as argued by SAIC analysts, that the large discrepancies between reconstructed doses and film badge readings

are due to unsubstantiated contamination on these ship's hulls that was not considered in dose reconstructions. However, this explanation invalidates the procedure of assigning reconstructed mean doses to unbadged participants on those ships (see Section 10.3), because all participants would have been exposed to that contamination and their doses would be underestimated. We believe that a better procedure would be to assign mean doses to unbadged participants on those ships on the basis of means of the distributions of film badge readings. If this procedure is not used, the upper bound factor that should be applied to reconstructed mean doses is about 6–8 on the USS CARPENTER and FLETCHER and about 25 on the USS O'BANNON when the bias in badge readings is taken into account.

In the case on the USS YUMA, we questioned an assumption by SAIC analysts that film badges recorded exposures that were not received by crew members, and we noted that reconstructed doses were based on measured exposure rates on a nearby island that could have misrepresented exposure rates on this ship. As on the USS CARPENTER, O'BANNON, and FLETCHER, we believe that reconstructed mean doses should be assigned to unbadged participants on the USS YUMA on the basis of the mean of the distribution of film badge readings. If this procedure is not used, the upper bound factor that should be applied to the reconstructed mean dose is about 7 when the bias in badge readings is taken into account.

The cases on the USS CARPENTER, O'BANNON, and FLETCHER summarized above do not call into question methods of dose reconstruction on ships when the presumably most important source of exposure could not be taken into account. However, these cases and the case on the USS YUMA do call attention to the potential for misuse of reconstructed doses in assigning doses to unbadged participants.

**16.2.1.4** *Operation CASTLE*. In some cases at Operation CASTLE where there are fewer than 20 film badge readings, most badge readings are above a nominal minimum detectable dose of 50 mrem and at least one reading exceeds the reconstructed mean dose by more than a factor of three (see Sections 11.1.1.1 and 11.2). As noted previously, we judged that a 3X upper bound factor is inadequate in those cases only if at least two badge readings exceed the reconstructed mean dose by more than a factor of three.

The five cases at Operation CASTLE where use of a 3X upper bound factor is inadequate involved exposures at various shots (see Section 11.1.1.1). In only one of the five cases was a

reconstructed dose based on measured exposure rates on a nearby ship or island. The highest film badge readings range from 0.4 to 1.3 rem. The upper bound factor that is required to give a reconstructed upper bound dose that exceeds at least 95% of all badge readings when the bias in badge readings is taken into account is about 10 on the USS ESTES during the period May 4–14, 8 on the USS COCOPA during the period May 8–18, 5 on the USS RECLAIMER during the period April 20–27 and on the USS MOLALA during the period April 12 – May 2, and 3.3 on the USS COCOPA during the period May 1–7. As noted in Table 16.2, the possible inadequacy of a 3X upper bound factor in the last case probably is not significant. Except in the two cases on the USS COCOPA, more than 40 badge readings were reported in published unit dose reconstructions; the number of readings in those cases provides confidence that the comparisons are valid indicators of the adequacy of a 3X upper bound factor.

In several cases at Operation CASTLE where use of a 3X upper bound factor was judged to be adequate, unusually high film badge readings in NuTRIS were not included in comparisons with reconstructed doses given in published unit dose reconstructions (see Section 11.1.1.2). Although the justifications for excluding those badge readings given by SAIC analysts may be valid, some readings apparently were excluded only on the grounds that they are much higher than readings that apply to typical crew members. We believe that the higher badge readings in NuTRIS is these cases raise questions about whether all relevant badge readings were included in comparisons with reconstructed doses in published unit dose reconstructions.

In an additional 27 cases on 13 ships at Operation CASTLE, film badge readings were not reported in published unit dose reconstructions, but at least five distinct badge readings are given in NuTRIS (see Section 11.1.1.2). In six of those cases, the highest badge readings in NuTRIS exceed the reconstructed mean dose by more than a factor of three. The published unit dose reconstructions do not provide an explanation of why badge readings in NuTRIS were not reported and compared with reconstructed doses. These additional cases were not taken into account in evaluating the adequacy of a 3X upper bound factor at this operation. However, these cases also raise questions about whether all relevant film badge readings were taken into account in comparisons with reconstructed doses in published unit dose reconstructions.

Although use of a 3X upper bound factor was found to be inadequate in several cases on ships at Operation CASTLE, it is important to emphasize that discrepancies between reconstructed doses and film badge readings on ships at this operation should not important in

adjudicating claims for compensation when cohort film badge readings are used to assign doses to unbadged participants.

**16.2.1.5** *Operation REDWING*. Environmental damage to film badges was an important problem at Operation REDWING, and we accepted all judgments by an SAIC analyst about badges that give reliable estimates of dose. In the one case on the USS SHELTON during the period April 20 – June 12 where use of a 3X upper bound factor on the reconstructed mean dose gives an upper bound that does not exceed at least 95% of the film badge readings that were judged to be reliable, an upper bound factor of at least 20 probably is required (see Section 13.3). An explanation of this discrepancy was not offered by the SAIC analyst. The reconstructed dose in this case was based on measured exposure rates on nearby ships or islands.

**16.2.1.6** *Operation HARDTACK I*. At Operation HARDTACK I, comparisons of reconstructed doses with film badge readings on ships were straightforward. In all cases where comparisons could be made, reconstructed doses were based on measured exposure rates on the ship. However, reconstructed doses could be compared with film badge readings in only a few cases. In many more cases, dose reconstructions were performed but results were not reported in SAIC memoranda (see Section 14.3.2). In some of those cases, reconstructed doses were based in part on assumptions about exposure rates that were adjusted to achieve agreement between the reconstructed dose and a mean film badge reading or similar assumptions on a nearby ship, but neither the reconstructed dose that would be obtained on the basis of unadjusted exposure rates nor the magnitude of the adjustments was reported. In other cases, the reconstructed dose during a period covered by film badge readings was not reported, and the mean badge reading was used in lieu of a reconstructed dose during the covered period. Since all participants at this operation were issued film badges, the primary purpose of dose reconstructions was to estimate doses during periods after badges were turned in and contaminated ships left the test area.

**16.2.1.7** *Summary of Evaluations on Ships*. Overall, the analyses on ships at PPG summarized in Table 16.2 indicate that use of a 3X upper bound factor on a reconstructed mean dose does not give an upper bound that exceeds at least 95% of all film badge readings in slightly more than 15% of the cases where meaningful comparisons could be made. The required upper

bound factor is only slightly greater than three in one case, which probably is not a significant discrepancy, about 4–5 in five cases, about 6–8 in five cases, and about 10 or more in four cases. Although comparisons could be made in many cases on ships, the number of cases at Operation HARDTACK I is limited. We believe that additional comparisons of reconstructed doses with film badge readings on ships at that operation would be informative if such comparisons are feasible. Other cases could be included if reconstructed doses that were estimated independently of badge readings but were not reported in SAIC memoranda are available.

Given the substantial number of cases on ships where use of a 3X upper bound factor was judged to be inadequate, we investigated whether the occurrence of those cases is correlated with the magnitude of doses or the lack of measured exposure rates on a ship. We considered all cases summarized in Table 16.2 except cases at Operation CROSSROADS, where causes of contamination and conditions of exposure on target ships were unique compared with exposures on ships at other operations. Special consideration was given to the four cases at Operation IVY where use of a 3X upper bound factor was judged to be inadequate, because the inadequacies probably are due mainly to factors that could not be taken into account in dose reconstructions and did not occur in other comparisons on ships at other operations. In investigating correlations with dose, we considered three ranges of dose: < 0.1 rem, 0.1–1 rem, and > 1 rem; doses were assigned to one of those categories on the basis of the reconstructed mean dose. Results of this investigation are summarized as follows:

- Cases where use of a 3X upper bound factor was judged to be inadequate do not clearly tend to occur more frequently when mean reconstructed doses are below 0.1 rem compared with the frequency of occurrence when doses are 0.1–1 rem. The only clear tendency is that inadequacies do not occur at doses above 1 rem.
- Cases where use of a 3X upper bound factor was judged to be inadequate generally tend to occur more frequently when exposure rates on a ship had to be estimated on the basis of measurements on nearby ships or islands compared with the frequency of occurrence when exposure rates were measured on a ship. However, the five cases at Operation CASTLE do not conform to the general tendency, because exposure rates were measured on the ship in four cases.

We also investigated whether the upper bound factor that would be required to give an upper bound of a reconstructed dose that exceeds at least 95% of all film badge readings in cases where use of a 3X upper bound factor was judged to be inadequate is correlated with the reconstructed mean dose or the lack of measured exposure rates on a ship. Cases on the USS CARPENTER, O'BANNON, and FLETCHER at Operation IVY were excluded on the grounds that the presumably most important source of exposure on those ships could not be characterized in dose reconstructions and, therefore, the magnitude of a required upper bound factor is not meaningful in regard to identifying possible problems with methods of dose reconstruction in cases of exposure to fallout on ships. When these cases are excluded, results of this investigation are summarized as follows:

- The required upper bound factor tends to be higher when reconstructed mean doses are below 0.1 rem. In all cases where the reconstructed mean dose is above 0.1 rem, the required upper bound factor is about 5 or less, whereas all cases where the required upper bound factor is greater than 5 occurred at doses below 0.1 rem.
- The required upper bound factor does not tend to be higher when exposure rates were measured on a ship. For example, exposure rates were measured on a ship in three of the four cases where the required upper bound factor is about 8 or higher, and exposure rates were not measured on a ship in half of the six cases where the required upper bound factor is about 5 or lower.

The first of these results conforms to expectations, but the second does not.

### **16.2.2** *Exposures of Other Units*

This section summarizes comparisons of reconstructed doses from exposure to residual gamma radiation with film badge readings for units at PPG that were not exposed on ships. Most of these comparisons involved participants who were exposed on residence islands for extended periods of time. A few comparisons involved participants who were exposed on other islands where test activities took place or as members of air crews. Those comparisons generally involved exposure for shorter periods of time.

The results of our analysis of exposures of other units at PPG to residual gamma radiation on the basis of reconstructed doses and film badge readings given in published unit dose reconstructions or SAIC memoranda are summarized in Table 16.3 and as follows:

- In all 41 cases where reconstructed doses were compared with at least five film badge readings, use of a 3X upper bound factor on a reconstructed mean dose gives an upper bound that exceeds at least 95% of all film badge readings. In 18 cases, most film badge readings are greater than 1 rem.

Some of these cases are discussed below.

**Table 16.3.** Summary of comparisons of reconstructed doses from exposure to residual gamma radiation with film badge readings at PPG – II. Comparisons for units on islands and other units not on ships[a]

| Operation | Doses < 1 rem | | Doses > 1 rem | |
|---|---|---|---|---|
| | Yes | No | Yes | No |
| CROSSROADS | 1[b] | | | |
| GREENHOUSE | 7 | | 1 | |
| IVY | | | | |
| CASTLE | 2 | | 1 | |
| REDWING | | | 3[c] | |
| HARDTACK I | 13 | | 13 | |

[a] Comparisons are based on readings of at least five film badges that were reported in published unit dose reconstructions or SAIC memoranda. "Yes" means that use of 3X upper bound factor on reconstructed mean dose gives upper bound that exceeds at least 95% of all badge readings; "No" means that use of 3X upper bound factor gives reconstructed upper bound that does not exceed at least 95% of all badge readings.

[b] Case involved crew members on photographic aircraft. All reconstructed doses are at or below nominal minimum detectable dose of 50 mrem, and all film badge readings are zero.

[c] In all cases, only mean film badge readings, but not their distributions, were reported in SAIC memorandum.

The case at Operation CROSSROADS is the only one in Table 16.3 that may not have involved exposure on a residence island or other island only. The reconstructed dose and film badge readings in that case are too low to allow a meaningful comparison.

The one case at Operation CASTLE where doses are above 1 rem involved participants stationed on Rongerik Atoll who were exposed to very high levels of fallout from Shot BRAVO (see Section 11.1.3). Doses in that case, which are about 35–50 rem, are more than an order of magnitude higher than doses in other comparisons at PPG, and reconstructed doses differ from comparable film badge readings by less than 15%.

In the three cases at Operation REDWING where only mean film badge readings, but not their distributions, were reported in an SAIC memorandum, we assumed that the highest badge reading is no more than a factor of two above the mean. This assumption is supported by the distribution of badge readings in NuTRIS in one case (see Section 13.3). In another case on a residence island at this operation, an SAIC memorandum reported that there was good agreement between reconstructed doses and film badge readings, but the memorandum does not give information on badge readings. NuTRIS also does not give any badge readings during the time period covered by the dose reconstruction. Since we could not evaluate the reported comparison, this case is not included in Table 16.3.

The cases of exposure on residence islands at Operation HARDTACK I comprise more than 60% of all cases in Table 16.3. In more than half of those cases, at least 20 film badge readings were reported (see Section 14.3.1), which provides confidence that the comparisons are valid indicators of the adequacy of a 3X upper bound factor. Mean badge readings in all cases range from about 0.2 to 2.4 rem, so the comparisons cover a wide range of doses.

Overall, the analyses summarized in Table 16.3 for island-based units and other units at PPG that were not exposed on ships indicate that use of a 3X upper bound factor on a reconstructed mean dose gives an upper bound that exceeds at least 95% of all film badge readings in all cases where meaningful comparisons could be made. There is no indication of important problems with dose reconstructions on islands.

### 16.3 Conclusions

Results of our analyses to compare reconstructed doses with relevant film badge readings for the purpose of evaluating the adequacy of applying a 3X upper bound factor to reconstructed mean doses or point estimates of dose with no uncertainty are summarized as follows:

- In cases of exposure to initial gamma radiation at NTS (18 cases) or exposure to residual gamma radiation in forward areas at NTS (38 cases) or on residence or other islands at PPG (41 cases) where a sufficient number of film badge readings were reported in published unit dose reconstructions or SAIC memoranda to permit meaningful comparisons, use of a 3X upper bound factor on a reconstructed mean or high-sided dose gives an upper bound that exceeds at least 95% of all badge readings in all cases except one when two cases of exposure to residual gamma radiation at NTS where the reconstructed mean or high-sided dose and many film badge readings are below a nominal minimum detectable dose of 50 mrem are excluded on the grounds that a comparison is not meaningful. Thus, use of a 3X upper bound factor usually was found to be adequate in cases of exposure on land at either theater of operation.

The one exception involved exposure of a small group of participants in Task Force WARRIOR (Project 50.1) to residual gamma radiation at Operation PLUMBBOB, Shot SMOKY at NTS. However, we do not believe that the large discrepancy between reconstructed mean doses and film badge readings for members of that group indicates a problem with methods of dose reconstruction at NTS. Rather, the cause of the discrepancy probably was an incorrect characterization of the radiation environment at the location where unexpectedly high exposures of the small group occurred that resulted from the lack of radiation survey data near that location; this is a rare occurrence that did not affect other comparisons at NTS. Furthermore, the discrepancy in this case does not have important consequences when doses that have been assigned to all members of this group are based on a film badge reading.

- In 93 cases of exposure to residual gamma radiation on ships at PPG where a sufficient number of film badge readings were reported in published unit dose reconstructions or SAIC memoranda to permit meaningful comparisons, use of a 3X upper bound factor on a reconstructed mean dose gives an upper bound that exceeds at least 95% of all badge readings in most cases, but not in a substantial number of cases. In 14 cases (about 15% of all cases) where use of a 3X upper bound factor was found to be inadequate, mean film badge readings are less than 1 rem and the required upper bound factor ranges from about 3.3, which probably does not indicate a significant discrepancy, to about 40. In an additional case at Operation CROSSROADS where some film badge readings exceed the

reconstructed dose by more than a factor of three, the high badge readings may represent exposures during activities that could not be reconciled with available records, and the significance of a comparison in this case is uncertain.

We also believe that discrepancies between reconstructed mean doses and film badge readings are potentially important in six of 27 additional cases on ships at Operation CASTLE where badge readings given in NuTRIS were not reported in published unit dose reconstructions. It could be informative to investigate whether badge readings in NuTRIS are valid in all 27 cases and, if so, to investigate the adequacy of a 3X upper bound factor in those cases.

We also investigated whether there are certain tendencies in cases on ships where use of a 3X upper bound factor was judged to be inadequate. We found that those cases do not clearly tend to occur more frequently when reconstructed mean doses are below 0.1 rem compared with the frequency of occurrence when doses are 0.1–1 rem, but that, with the exception of cases at Operation CASTLE, those cases tend to occur more frequently when exposure rates on a ship had to be estimated on the basis of measurements on nearby ships or islands. We also found that the required upper bound factor tends to be higher when the reconstructed mean dose is below 0.1 rem than at higher doses, but that there is no noticeable tendency for the required upper bound factor to be higher when exposure rates were not measured on a ship.

In the four cases on ships at Operation IVY where there are large discrepancies between reconstructed mean doses and film badge readings (the required upper bound factor is about 6–8 in three cases and 25 in the fourth), we believe that the cause of the discrepancy in three cases is an incorrect characterization of the radiation environment that resulted from a lack of measured exposure rates on the ships and an inability to estimate the extent of likely contamination on the ship's hulls, and that the causes of the discrepancy in the fourth case may have been a lack of measured exposure rates on the ship and a questionable assumption in the dose reconstruction that film badges recorded exposures that were not received by crew members. These situations apparently did not occur in other comparisons on ships, and the discrepancies in these cases do not necessarily indicate important problems with methods of dose reconstruction on ships.

The finding of large discrepancies between reconstructed doses and film badge readings in a substantial number of cases on ships at PPG leads us to conclude that, whenever possible, doses to unbadged participants on a ship should be assigned on the basis of badge readings for

other participants on that ship, rather than a reconstructed dose, even when discrepancies are unimportant. For example, the large discrepancies in several cases at Operation CASTLE should not be an important concern when cohort badge readings generally are used to assign doses to unbadged participants. However, information in NuTRIS indicates that reconstructed doses have been assigned to unbadged participants on ships at Operations GREENHOUSE and IVY, and we believe that this procedure should not be used when mean doses can be estimated on the basis of distributions of film badge readings.

A related issue concerns the treatment of film badge readings in a particular unit that are substantially higher than most badge readings. The presence of a few outlier badge readings was noted in several published unit dose reconstructions at NTS and PPG. In some cases, the unusually high badge readings were explained by documented activities of a few participants that differed from the activities of most members of a unit. In other cases, SAIC analysts simply asserted that unusually high badge readings did not represent exposures that were taken into account in a dose reconstruction and, therefore, should not be used in evaluating the extent of agreement between a reconstructed dose and badge readings. We do not take issue with these arguments. However, these situations raise a concern about whether badge readings that appear to be outliers should be taken into account in assigning doses to unbadged participants. Information in NuTRIS indicates that reconstructed doses often have been assigned to unbadged participants, and that higher outlier badge readings have not been considered. This approach seems appropriate when it can be established with reasonable certainty that unbadged participants did not engage in unusual activities that could have resulted in unusually high doses. However, we believe that this approach is difficult to justify when an unbadged participant's activities are uncertain. In such cases, we believe that doses should be assigned to unbadged participants on the basis of means of distributions of all badge readings in a unit, including outliers, rather than a reconstructed dose. By taking outlier readings into account when there is little evidence to justify their exclusion, unbadged participants would be given the benefit of the doubt in their assigned doses.

In comparing reconstructed doses with film badge readings, we attempted to use badge readings given in NuTRIS in addition to badge readings that were reported in published unit dose reconstructions or SAIC memoranda. However, we encountered several problems in attempting to obtain definitive information on film badge readings in NuTRIS (see Section 1.5), and it was

difficult to conclude that badge readings in NuTRIS that were not reported in published unit dose reconstructions or SAIC memoranda could be used reliably in our analysis. Although we compared badge readings in NuTRIS with reconstructed doses in some cases, those comparisons were not included in our evaluations of the adequacy of a 3X upper bound factor.

We do not mean to imply that difficulties we encountered in using NuTRIS indicate important problems with the database; NuTRIS was designed for different purposes than we attempted to use it for. However, limitations in the usefulness of NuTRIS to our analysis led us to conclude that meaningful comparisons of reconstructed doses with film badge readings could be made only when badge readings were reported in published unit dose reconstructions or SAIC memoranda. Possible exceptions involved exposures of observers at Operation TEAPOT, Shots BEE, ESS, and APPLE II, where a substantial number of film badge readings in NuTRIS were not reported in published unit dose reconstructions and the published report indicated only that available film badge data were inadequate (see Section 5.1.2.2), and exposures on several ships at Operation CASTLE, where a substantial number of badge readings in NuTRIS were not reported in published unit dose reconstructions and neither NuTRIS nor the published report provide information to indicate that those badge readings do not represent exposures of average crew members (see Section 11.1.1.2).

We should also note that useful information was obtained from NuTRIS. Information in NuTRIS allowed us to identify situations where reconstructed doses may have been assigned inappropriately to unbadged participants. In addition, information in NuTRIS gave no indication that there are additional types of exposure situations where use of a 3X upper bound factor is inadequate beyond the situations that were identified on the basis of reconstructed doses and film badge readings in published unit dose reconstructions and SAIC memoranda.

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